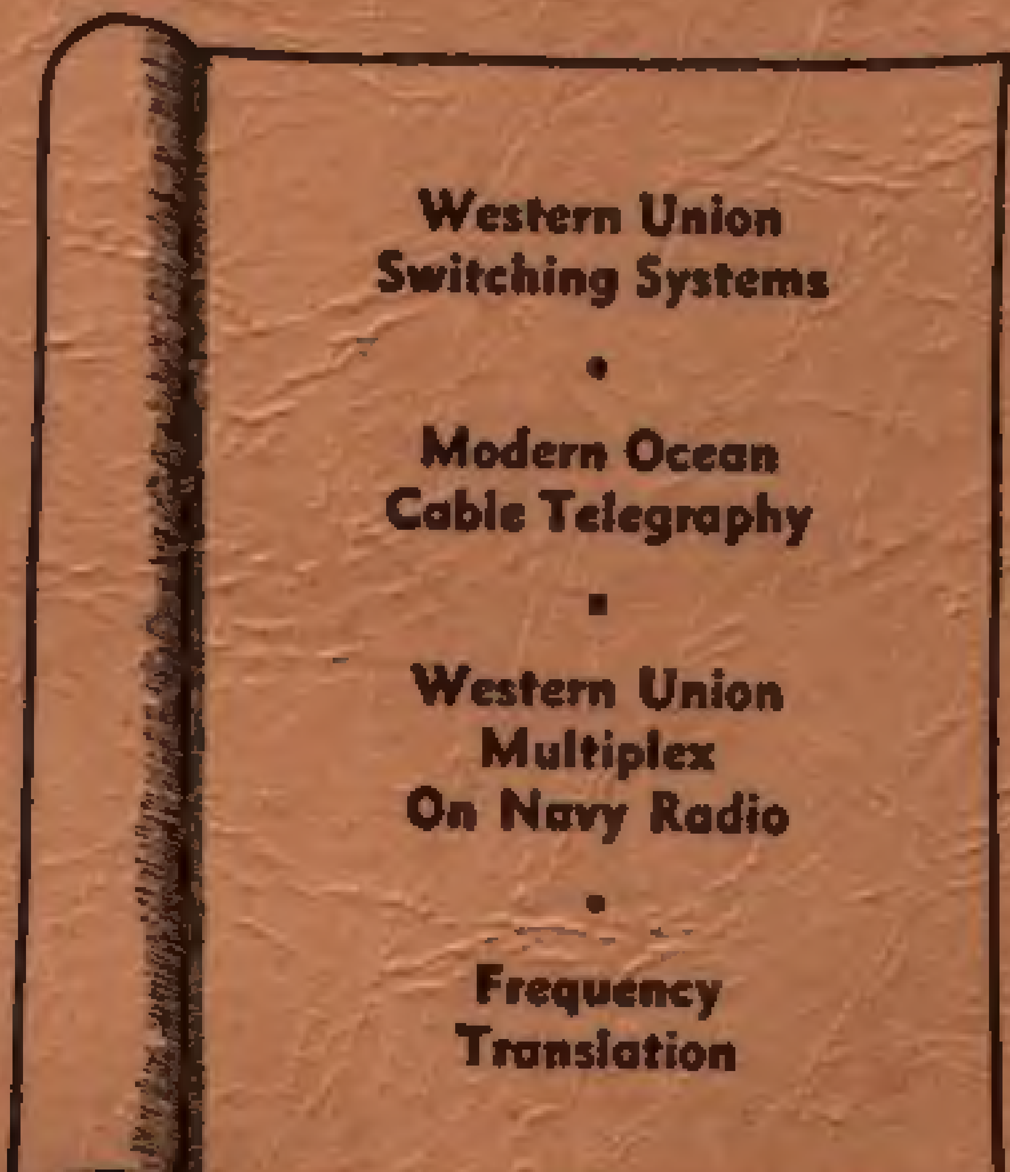
WESTERN UNION

Technical Review



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WESTERN UNION **TECHNICAL REVIEW**

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Presenting Developments in Record Communications and Published Primarily for Western Union's Supervisory, Maintenance and Engineering Personnel.

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To Readers of the Technical Review:

The TECHNICAL REVIEW *in this new format enters a period of greater usefulness to Western Union and its people, by disseminating technical information more quickly and in better form, especially among the men and women who are carrying out the Company's highly important mechanization program.*

As the program for mechanization and plant improvement gains momentum on a national basis, there is an increasing need that supervisory and maintenance employees be kept well-informed about Western Union's scientific thinking and technological progress.

The TECHNICAL REVIEW *is intended to furnish basic information for all these technicians and for other employees interested in technological progress in the telegraph industry. We hope that the* TECHNICAL REVIEW *will help to broaden the knowledge and capabilities of all Western Union operating and construction personnel.*

Through that improvement of themselves, members of the Western Union family will be able to take a more effective and satisfying part in the fast moving progress of the telegraph industry. As more and more units in the new, streamlined national telegraph network are installed and skillfully manned, Western Union will render even better service to the public and be an even better place to work.

January 1, 1948.

President.

The Development of Western Union Switching Systems

R. F. BLANCHARD and W. B. BLANTON

A revolutionary change in the telegraph industry is quietly but rapidly approaching completion. The mechanization program which Western Union has undertaken and scheduled for completion about the end of 1950 is much more significant and penetrates more deeply into the fundamentals of telegraphy than is generally realized. This article on switching, and others which will follow, deal with but one phase of the Company's greater plan to bring into being on a nation-wide scale a completely new telegraph system. It will be helpful to a better understanding of matter discussed in these articles if the reader can visualize this new system and the part which switching plays in it.

The telegraph industry was built up around more than 100 area centers or "relay" offices. Each of these centers served tributary offices in its immediate vicinity over direct telegraph lines and relayed telegrams from that area to other area centers where they were again relayed either to point of destination, or to still other area centers until they could be transmitted to point of destination. Thus a telegram might transit through two, three or more of these relay offices depending upon the geographical location of the originating point and the destination. The number and location of relay offices had been established largely by conditions that prevailed in the early days of the industry when difficulties in obtaining adequate operating margins limited the operable length of circuits. These relay offices grew into a nation-wide system inter-connected by approximately 1,600,000 miles of single-wire or ground-return circuits. At each relay office telegrams were manually received by operators who gummed the printed tape to receiving blanks. Route clerks and route aides directed and carried them to outgoing circuits, where other operators perforated tapes for transmission on to other stations.

The mechanization plan was approached from the viewpoint of creating a completely new telegraph system embodying the most progressive ideas and techniques known to the industry. The distribution system for the entire country was scientifically plotted to provide the most direct paths from any given city, town, or hamlet to any other point with a minimum number of handlings. To bring about this condition the 48 states were divided into 16 geographical areas. Each area comprises one or more entire states in which all localities having telegraph service will have direct connection to an "area center" which serves them exclusively. Each area center will have direct circuits connecting it to each of the other 15 area centers. Thus, no telegram will transit through more than two area centers enroute from origin to destination, while many will transit through but one. Since the area centers will be located in the larger cities of the country, the greatest interchange of traffic will be between these centers and, therefore, while such traffic may be said to transit through two area centers, it will be handled on direct circuits. Similarly, much of the traffic that originates or terminates in one of these area center cities will be exchanged with localities within its own area, due to the fact that such cities also generally represent the commercial and industrial centers for those areas. Here again, telegrams will be handled over direct circuits between points of origin and destination. By careful analysis of the interchange of communications between cities and areas, the

system has been designed to provide direct point-to-point service on a majority of all telegrams.

The foregoing rearrangement of the nation-wide distribution system was made possible by, and is going forward coincident with a plant facility expansion program of tremendous magnitude. Approximately 1,100,000 wire miles or 69% of existing ground-return trunk circuits will be supplanted by 2,750,000 carrier channel miles of facilities to be derived from operation over wires and/or radio beam transmission. The net increase in trunk facilities of 1,650,000 miles represents a 103% gain. This will be used to increase materially the number of channels available between points now having direct connections with each other; to increase the number of points that will have such direct connections; and to provide spare and emergency fall-back facilities on a scale that has been economically impracticable heretofore. Metallic circuit and radio beam operation, due to relative freedom from earth currents, inductive disturbances, and the effects of weather conditions, will insure a stability of operation and continuity of service that is not possible over ground-return circuits. These improvements will in turn have a beneficial influence on the accuracy and speed of transmission with which telegrams are handled.

New central offices have been engineered and are being installed at the 16 area centers which form the nucleus of the new distribution system. These new offices are designed to accommodate the considerable increase in circuit terminations brought about by the distribution system described above, and to have potential message handling capacities based upon projections of favorable future developments in the communications field. Switching systems of the most modern design are being installed in these offices and the time required for a telegram to transit through these offices will be greatly reduced. All transmission errors due to manual handling in relaying telegrams from one circuit to another will be eliminated.

Switching systems will also be installed at several other large cities which are not scheduled to be area centers. These large terminal offices will be exceptions to the "area center" plan of distribution to the extent that they will have direct connections to various areas. A modified form of switching will be used to expedite the handling of telegrams originating and terminating in those cities. Plans contemplate the possibility of extending switching operation to many smaller cities.

The mechanization program outlined above was developed as the practical application of improvements worked out in the laboratories on carrier circuit and radio beam operation, and the invention of reperforator switching as a practical method of operation. Their combination into an integrated telegraph system is the product of many joint efforts, after first compiling and analyzing massive volumes of data on traffic loads, outside plant facilities, and operational costs. The goal of the mechanization program was set forth clearly when the "plan" was adopted as: "...to provide the best possible service at the lowest possible rates consistent with the interest of the public and the Company."

In accordance with the foregoing plan, the 16 area centers or "relay" offices and the tributary areas served by them will be as follows:

Area Centers	Tributary Areas
*ATLANTA:	South Carolina; Georgia; Florida
BOSTON:	Massachusetts; Maine; Vermont; New Hampshire; Rhode Island; Connecticut
*CINCINNATI:	Ohio; West Virginia; Kentucky; Tennessee
*DALLAS:	Texas
DENVER:	Wyoming; Colorado; Utah; New Mexico
DETROIT:	Michigan; Indiana
KANSAS CITY:	Missouri, except St. Louis; Nebraska; Kansas; Oklahoma
LOS ANGELES:	Los Angeles; Arizona
MINNEAPOLIS:	Wisconsin; Minnesota; Iowa; North Dakota; South Dakota

NEW ORLEANS:	Louisiana; Alabama; Mississippi
*OAKLAND:	California, except Los Angeles; Nevada
*PHILADELPHIA:	Pennsylvania; New Jersey; Delaware
PORTLAND (OREGON):	Oregon; Washington; Idaho; Montana
*RICHMOND:	Maryland; Virginia; North Carolina
*ST. LOUIS:	St. Louis; Arkansas; Illinois
SYRACUSE:	New York (including Long Island)

*Offices installed and in operation prior to 1948.

messages in the form of perforated tape, and to physically carry the tapes to the proper outgoing trunk terminals where they would be manually inserted into the usual type of line transmitters. It soon became apparent that the handling of short lengths of perforated tapes involved problems that differed too greatly from those of existing methods to combine the two successfully. In projecting the possibilities for an increased speed in handling telegrams and for a production increase commensurate with the cost of apparatus, it was decided that any system which

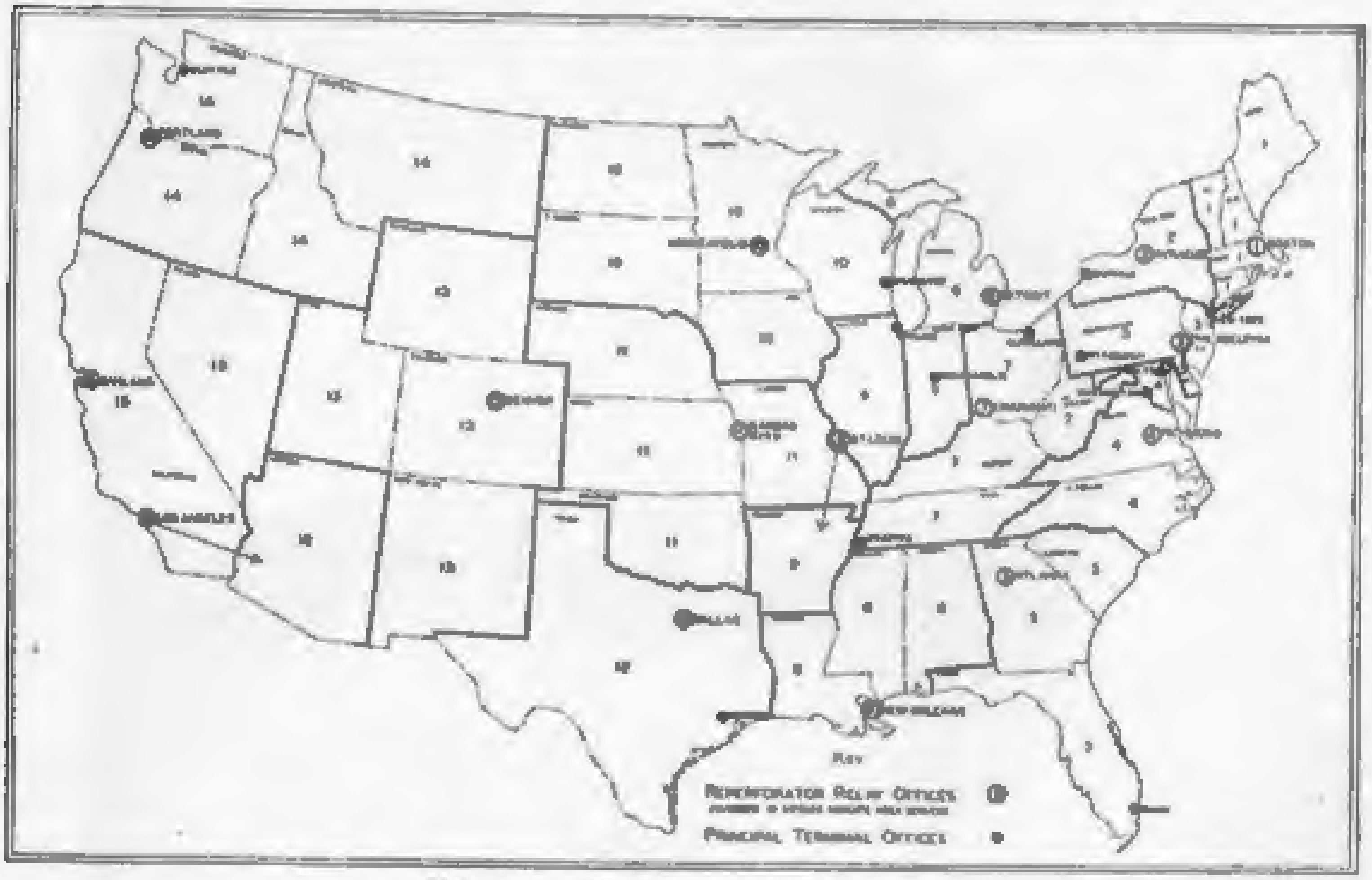

Figure 1. Block state routing areas

HISTORICAL BACKGROUND OF REPERFORATOR SWITCHING

A brief resume of the "why's" and "wherefore's" of reperforator switching and the various stages of its development as they appeared in the first and succeeding installations, will give the reader a clearer understanding of the system to be described in detail in this series of articles.

The first serious study of reperforation was undertaken in 1933. It was then proposed to use reperforators to receive retained the separate elements of reception, physical transportation across the office, and transmission, would not offer sufficient inducement to justify the development of a radically new method of operation. From these conclusions two basic principles of the new system were established:

1. A new method of operation should be developed in which reperforators would be used as the recording device on all printing telegraph circuits entering an office;

2. Retransmission should be performed at the same position at which telegrams were received and the distribution of telegrams to proper outgoing circuits should be through turrets utilizing the plug and jack principle.

These conclusions emphasized the desirability of having reperforators that would produce both printed and perforated tapes simultaneously; of establishing operating routines for switching telegrams in chronological order as received; and of maintaining an unbroken sequence of reperforated tape at the switching position.

Other essential features of a new method of operation would be the continued use of sequence numbers on telegrams transmitted to other offices, as a safeguard against transmission failures; ability to use a single transmitter at each switching position that could transmit into either start-stop (teleprinter) or synchronous (multiplex) circuits; and transmission away from receiving positions at a higher rate of speed than reception, in order to overcome the effects of "holding time" when a desired circuit should be found to be busy, and of time consumed in performing the switching operation.

In order to meet these requirements, reperforators also were placed on the sending sides of all line circuits. Intra-office transmission from receiving positions to these reperforators on sending sides was adopted in preference to retransmission direct to line. Reperforators on the sending sides of line circuits would be connected by intra-office circuits to jacks in the switching turrets. These sending reperforators would feed their perforated tape directly into adjacent transmitters which would be constantly connected to their individual line circuits. This arrangement made practicable the use of automatic numbering machines which could be caused to pre-empt the intra-office circuit whenever a connection was established through the switching turret, transmit the next sequence number of the line circuit with which it was associated, and then release the intra-office circuit and permit the telegram for which the connection was established to be transmitted. Sequence numbers would thereby be maintained, and the perforated tape at the sending position would record both the automatically injected number and the telegram with which it was associated. All purposes of the sequence number would thereby be fulfilled. Intra-office transmission would always be from a uniform type of transmitter without regard to the type of line circuit to which the message was destined; and the transmitters on line sending positions would be either teleprinter or multiplex according to the types of line circuit to which they were continuously connected. Intra-office transmission speed could be increased without affecting the speed of line circuit operation.

In order that the switching function might be performed without continuous supervision, it would be necessary to have controls in the intra-office circuit to permit switching clerks to establish potential connection to "busy" circuits and have the actual connection completed by the functioning of purely automatic equipment whenever the desired circuit became available; and to perform a disconnect operation and stop the transmitter at the switching position at the end of each message by the functioning of automatic equipment.

Notwithstanding the many changes and improvements that have been incorporated in the reperforator switching system from time to time, the foregoing fundamental principles have remained unchanged and will be found in all reperforator offices.

Ft. Worth, Texas

The first trial installation at Fort Worth did not have sending position reperforation nor automatic numbering machines on all line circuits, and the transmission speed away from receiving reperforators was at the rate of only 65 words per minute or standard line speed. Experience quickly proved earlier assumptions that sending position reperforation and automatic numbering machines would have to be used on all line circuits. The imperative need for higher transmission speed

away from receiving reperforators also was conclusively proved. Subsequently, the system at Fort Worth was remodeled to incorporate these features.

The results from this installation were very gratifying. The handling of telegrams was speeded up considerably. The production of switching clerks indicated a capacity to switch 200 messages per hour during peak hours, the equivalent of 400 message-handlings per hour under manual operation. Production over a period of a month was at the average rate of 121 switches per hour, or the equivalent of 242 message-handlings in manual operation. This was approximately four times the best production to be expected of manual operation.

While the trial at Forth Worth demonstrated the correctness of the basic principles of reperforator switching, it also brought out the need for further refinements. An intra-office transmission speed higher than the 90 words per minute which had been used in the remodeled installation at Fort Worth would be required in larger offices where line circuit loads would be greater. It was also felt desirable to incorporate a means by which telegrams of an especially urgent character could be expedited and a means by which deferred rate telegrams could be temporarily side-tracked during peak load periods.

Richmond, Va.

Following the experience gained from the trial installation at Fort Worth, in which it was conclusively demonstrated that an operable and economically profitable switching system could be designed, engineering was directed toward the development of such a system that would be applicable in the largest offices where circuit loads would be denser and the number of circuits involved would be far more numerous than was the case at Fort Worth. The goal to be sought was a switching system that would be wholly independent of a favorable local condition that might exist in one or a few offices. The principles to be embodied would be universally applicable and only the number of units of equipment to be installed would vary with the size of office.

Working along this line, an intra-office transmission speed of 125 words per minute (approximately double the speed at which telegrams are received) was made possible by adoption of a five-wire intra-office system. This would permit the simultaneous transmission of all five impulses of each character. While it might appear that this makes possible a speed five times as fast as line transmission, in practice the mechanical and electrical functioning of transmitters and reperforators introduces factors which limit the actual operable speed to approximately twice that of line transmission. It was necessary to develop multi-conductor jacks and plugs with which to operate the five-wire system.

"Printer-perforators" were designed which used but one tape and which printed each received character immediately above the perforated holes. From an operating viewpoint this was a major improvement for it made possible quick scanning of incoming telegrams by the switching clerk and eliminated the possibility of asynchronous tape handling that might occur if separate tapes were used for printing and perforating.

Double-decked equipment tables were designed to conserve floor space and to condense into the smallest practicable area the number of circuits to be served by a switching clerk. All line receiving reperforators were grouped in one section of the room forming an exclusive switching aisle, and all line sending positions were grouped in another section of the room, forming an aisle requiring only supervisory attention and patrol. Special tables were designed for the use of supervisors and testing and regulating attendants, and intra-office telephones were provided for ready communication between various sections of the operating room. Circuits were designed that would operate signal lamps to indicate when messages were awaiting attention of the switching clerk; when intra-office transmission had been completed and the plug could be removed from the jack; when there was a tape jam or tie-up in the send-

ing position reperforators requiring instant attention; and when the amount of unused tape in reperforators and printer perforators was becoming dangerously low.

A system of reperforator switching which embodied all of these ideas was installed at Richmond, Virginia. This installation was an immediate success. Under every test of practical operation it demonstrated its superiority over manual operation in accuracy, speed, and production. More important, it proved conclusively that the principles upon which it had been engineered were applicable with no fundamental change in offices of much greater size.

Figure 2. Main switching aisle—Richmond, Va.

Atlanta, Ga.

Experience gained from operation at Richmond, however, developed still other ideas for refining the system along lines which would reduce installation costs and facilitate supervision and operation. One major development was that in actual operation, telegrams were disposed of so rapidly that special "side-tracking" positions into which deferred telegrams could be switched were unnecessary. Elimination of these positions would decrease the cost of the system materially. With this modification, switching was adopted as the standard method of operation for central offices.

Studies were started to select other offices where switching systems would be installed, and to determine the preferential order in which they should be converted. It was apparent that the large area centers or "relay offices" would be the logical field. Their preferential status would be determined by the ratio of "relay" to "non-relay" traffic handled by each office. In the sense used here the term "relay" has a special significance somewhat different from that which is usually meant. In a switching system, any telegram received over one printing telegraph circuit for retransmission over another printing telegraph circuit can be

switched profitably because the switching operation replaces all former manual operations. This class of traffic is termed "relay". Telegrams which are received over Morse telegraph circuits, telephones, or by tube, prior to the switching operation must be manually perforated into tape form at "local" sending positions in the same manner that it would be done under manual operation; and, going in the opposite direction, telegrams received over printing telegraph circuits on reperforators and which must be dispatched out of the office by Morse, telephone, or tubes, must be switched to "local" receiving positions where they will be recorded on gummed tape, gummed to receiving blanks, timed, and released for further handling, in the same manner that those operations would be performed under manual operation. This traffic is termed "non-relay", or "local".

From the foregoing it will be apparent that while switching equipment must be installed to provide for a switching handling on all telegrams, both relay and local, savings are derived only on those classified as "relay"

A list of offices suitable for switching systems was compiled. The most advantageous place appeared to be Atlanta, Georgia, which was selected as the first major relay office to be converted to the new method of operation. A number of innovations and refinements were incorporated as the work progressed. It had been found that intra-office telephone communication could not keep pace with the new tempo of operation. Instantaneous interchange of information between sections of the operating room would be mandatory in order to maintain the fast pace which the new system had established. Microphones and loudspeakers were substituted for the intra-office telephone as the communicating system between various sections of the office. It was also felt that a blackboard which had been used at Richmond for posting "alternate routings" during emergencies, would not be adequate in large installations such as that proposed for Atlanta. Therefore, electrically operated routing boards were developed for installation at various points in an office where they would be visible to all switching clerks. Emergency routings made necessary through circuit failures or other causes could be posted on these boards electrically from a central supervisory position. In order to secure greater usage of receiving positions, a line-finding concentrator that would connect any one of eight lightly loaded lines to any one of four printer-perforator receiving positions had been used at Richmond For Atlanta three such concentrators, each accommodating twelve lightly loaded tributary or branch lines on four positions, were provided

A special switching position was developed for handling multiple address, or "book" telegrams. These "books" consist of a number of telegrams, all of which have the same text and signature but each of them having a different addressee In handling these books at relay offices, routines provide that outline copies of the text and signature be transmitted in duplicate by the out station, followed by all of the addresses. In the new system the routine of the relay office would provide that after comparing the two tape outline copies of the text for accuracy, an endless loop would be made of one of them by joining the ends together. This endless loop text tape would be placed in one of a pair of transmitters and the address tape in the other at a special "book" position. The switching clerk would set up a connection at the switching turret for the first address, and one transmitter would send the text tape, after which it would stop and transfer the circuit to the other transmitter which would send the address and then stop. The same operation would be repeated for the next and all subsequent addresses, thus transmitting all telegrams in the book from one text tape

St. Louis, Mo., Dallas, Tex., and Oakland, Calif

There was little change in the switching systems installed at these three offices from that described for Atlanta, except that provision was made for switching messages to tie-line patrons through a secondary switching unit

Figure 3 Main switching aisle—St. Louis, Mo

Philadelphia, Pa., and Cincinnati, Ohio

These two cities represent the last installations prior to 1948. Two major changes were incorporated in them—"Push-button" switching from all line receiving positions, and "automatic switching" from local sending positions

In push-button switching, the turrets consist of rows of push-buttons each labeled with the name of the circuit that it serves. This replaces the former type of turret which used multi-conductor plugs and jacks. The number of circuits that can be accommodated in a turret of practicable size is much greater than formerly The ease and speed with which the switching function can be performed are increased also.

In automatic switching from local positions to trunk circuits, a route clerk places on each telegram an indicator designating the proper outgoing circuit. Transmission is directed into these circuits by the automatic functioning of relay banks and stepping switches. Adoption of this method eliminates the need for switching turrets and switching clerks formerly required to handle this portion of the traffic. Time consumed in establishing connections is cut approximately in half, and several thousand manual switching operations daily are eliminated in each office

Boston, Mass., Denver, Colo., Detroit, Mich., Kansas City, Mo., Los Angeles, Calif., Minneapolis, Minn., New Orleans, La., Portland, Ore., Syracuse, N. Y

A switching system known as Plan 21-A will be used in these offices, which are scheduled for installation subsequent to January 1, 1948. Telegrams originating at tributary and branch offices, as well as those from local positions, will be automatically switched into trunk circuits in a manner similar to that which is now used for local positions only at Philadelphia and Cincinnati. In the opposite direction, from trunks to tributaries, branches

and locals, push-button switching will be used

With this introductory review of the development of reperforator switching as a new method of central office operation and its important contribution to the mechanization program, we will now proceed with a detailed description of the system.

DESCRIPTION OF PLUG AND JACK SWITCHING SYSTEM

In general, a switching unit must provide facilities for handling messages which are received into and sent out of area centers over:

1. Trunk circuits which connect the area center to other area centers and to certain large terminal offices,
2. Tributary circuits which connect the area center to the towns and cities within its own area,
3. Branch office circuits which connect the area office to branch offices located within the same city;
4. Public telephone, Morse circuits and pneumatic tubes,
5. Tie-line circuits which connect the area center to patrons' offices.

Figure 4 shows the principal equipments and circuit arrangements that comprise a plug and jack switching unit for handling messages received and sent over the five groups of facilities just described. Only one of each of the various equipment and circuit arrangements has been included in the diagram. It will be appreciated that in an actual installation there would be a sufficient number of each of these arrangements to meet the requirements of the particular installation

Each trunk, tributary and branch office circuit (Items 1, 2 and 3 above) except very lightly loaded tributaries, consists of a receiving and a sending channel which may be operated simultaneously. The receiving and sending channels for a trunk or tributary circuit are derived by using either a duplexed teleprinter circuit, or a receiving and sending channel of a duplexed multiplex circuit. In the case of branch offices which are located within the same city as the area switching office two line wires are used, one exclusively for receiving from the branch office and the other exclusively for sending

Receiving sides of trunk, tributary and branch office printing telegraph line circuits (operated either teleprinter or

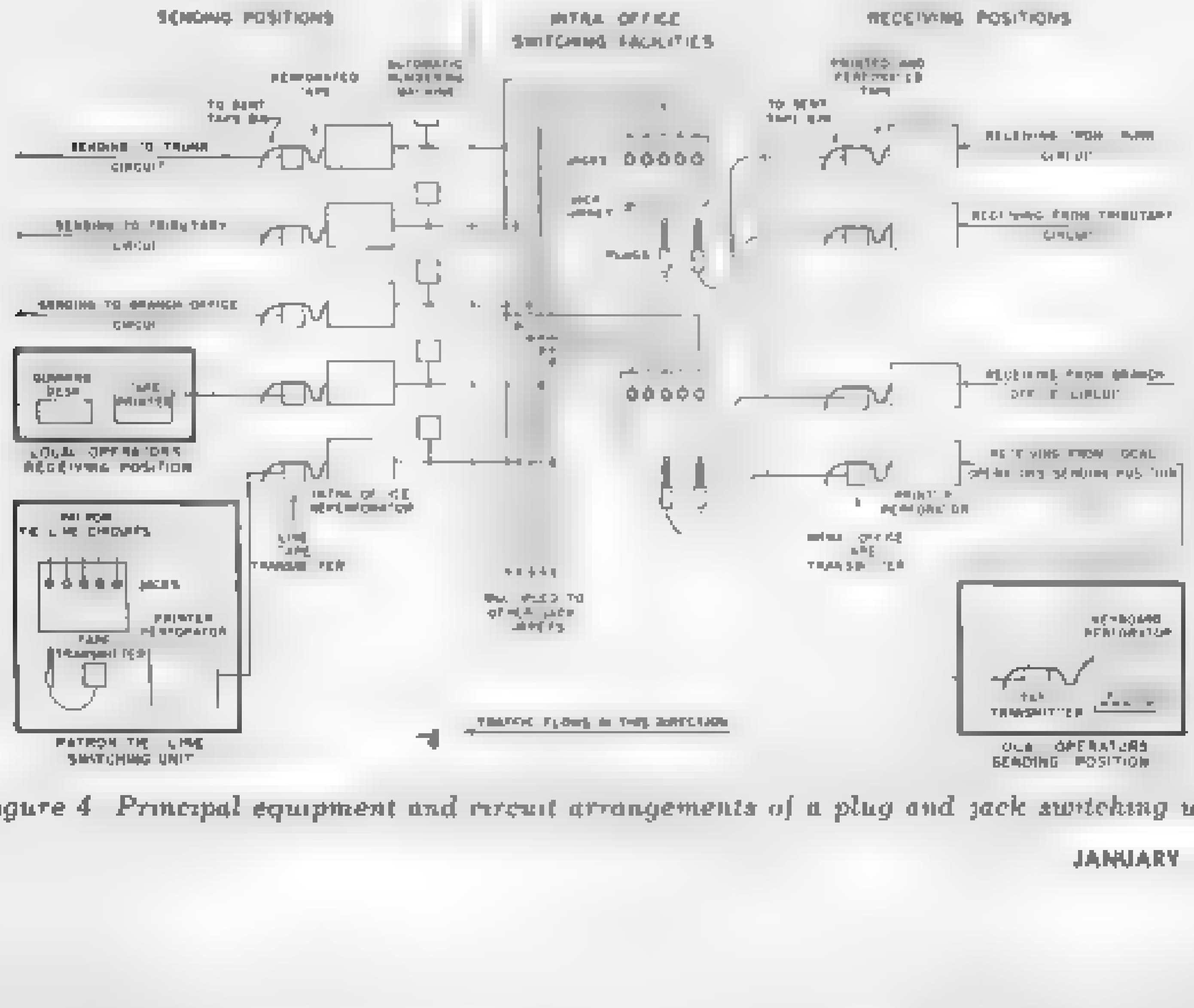

Figure 4 Principal equipment and circuit arrangements of a plug and jack switching unit

multiplex), are terminated in printer-perforators at receiving positions. A printer-perforator which operates "start-stop" is used at teleprinter positions, and a printer-perforator that operates from a multiplex synchronous distributor is used at multiplex positions.

Sending sides of trunks, tributary and branch office printing telegraph line circuits (operated either teleprinter or multiplex), are terminated in tape transmitters at sending positions. Each sending position is arranged so that by removing or adding wiring straps, it can be converted to either teleprinter or multiplex operation. For teleprinter operation, a distributor-transmitter is provided which transmits "start-stop" code signals over the line wire, while for multiplex operation, the tape transmitter is connected over eight wires to the multiplex synchronous distributor which transmits to the line wire.

Messages received by telephone, Morse and pneumatic tube (Item 4 above) are recorded or received in printed form, or in the patron's own handwriting. Before these messages can be switched they must be transmitted into the switching unit over a local printing telegraph circuit. Local operators' sending positions are provided for this purpose. One such position, equipped with a keyboard perforator and a tape transmitter, is shown in the lower right side of Figure 4. These messages are handed to local sending operators who, by manipulating the keyboards of perforators, prepare them in perforated tape form. This tape flows through the transmitter at the operator's position and the messages are transmitted into a printer-perforator at the receiving position in the switching unit. They are then switched to the proper outgoing circuits.

In the opposite direction, messages are received in the switching unit which must be converted into printed form at local receiving positions for delivery from the area center by telephone, Morse or tube. In order to maintain the intra-office transmission speed of 150 words per minute away from receiving positions and to maintain a system of sequence numbering, these messages are switched to intermediate reperforator positions (see the fourth from the top sending position in Figure 4) which retransmit them into tape printers located on local operators' receiving positions at a speed of 70 words per minute. Messages received at a local receiving position are printed on a tape which is gummed on the under side. The local receiving operator "gums" this tape on a message blank, thus producing the message in printed form. The printed messages are then conveyed to the telephone, Morse, or pneumatic tube departments to be forwarded on to their destinations.

Tie-line circuits (Item 5 above) connect the Western Union office to the offices of patrons in the same city who are large users of telegraph service. Most of these tie-lines are printing telegraph circuits, and there are no insurmountable technical reasons why these circuits could not be directly connected into a switching unit. There are, however, certain practical reasons why this is not desirable as a general practice. The requirements in regard to accuracy, form of message, and observance of routines necessary in switching operation, make it impracticable at this time to retransmit through the switching unit telegrams received over tie-lines, until they have been edited and put into proper message form. These telegrams are received on printers and are then handled through the local transmitting position in the same manner as messages received by telephone, Morse, and tube.

Going in the opposite direction, it is undesirable to switch directly to tie-lines from the switching unit, because the inclusion of tie-lines in the switching turret would double or triple the size of those turrets and would correspondingly increase the amount of routing information that switching clerks would have to learn. It has been found preferable to switch teleprinter tie-line traffic over intra-office circuits into "secondary" switching units (lower left-hand side Figure 4), where it again appears in the form of printed and perforated tape. Tie-line switching clerks at this secondary switching unit, reswitch the tapes through tur-

rets which serve tie-line patrons exclusively

Principal Elements of a Switching Unit

The switching unit in an area center or "relay office", can be thought of as consisting principally of line receiving positions, line sending positions and intra office switching facilities. The intra-office switching facilities provide circuit arrangements that permit establishing, for each received message, an intra-office connection from any receiving position to any sending position. As is readily evident from its terminology, intra-office switching by the plug and jack method requires that a switching clerk insert a plug into a jack in order to establish an intra-office connection. Figures 5 and 6 show the type of line receiving positions, jack turrets, and line sending positions used in St. Louis Dallas, and Oakland which were the last plug and jack installations. Earlier plug and jack installations at Richmond and Atlanta differ in some details but all of them have followed the same general pattern.

Line Receiving Positions and Associated Jack Turrets

The principal items of equipment at a line receiving position comprise the line receiving printer-perforator (Figure 7) the intra-office tape transmitter (Figure 8) which is connected to a cord and plug mounted at the turret, a tape accumulator; and the signal lamps, push-buttons and toggle switches which serve various supervisory and trouble-warning functions. These receiving positions are arranged on double-decked tables, and are grouped two or four positions on each side

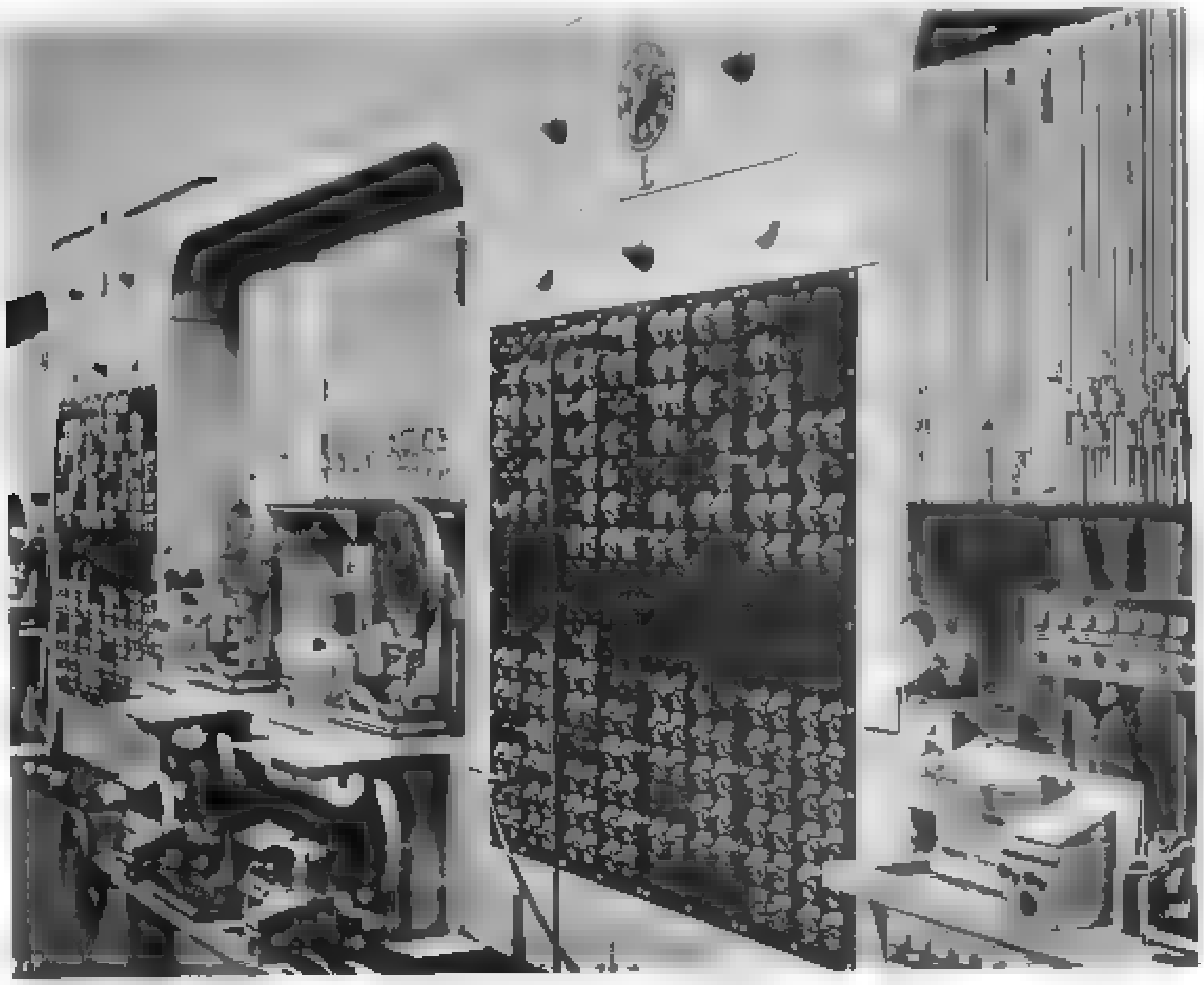

Figure 5. Line receiving positions and jack turrets

Figure 6. Line sending positions

of a jack turret, thus providing four-position or eight-position turrets as desired In some cases, because of space conditions, a six-position turret is installed. Receiving line circuits having heavy message loads (generally trunk circuits) are terminated in receiving positions at four-position turrets, and the lighter loaded line circuits terminate in receiving positions at eight-position turrets

A row of jack turrets and their associated receiving positions are installed on each side of a switching aisle, the two rows of turrets and positions facing towards the aisle. The relays, resistors, connecting blocks and associated equipment required in the receiving position circuit arrangements are mounted on the rear of the double-decked table. A smal. aisle is provided behind each row of tur-

rets and receiving positions for testing, regulating and maintenance purposes.

At least one jack is provided in each turret for each sending destination. On receiving positions where the traffic load to certain destinations is heavy, two (and

Figure 7 A line receiving printer-perforator

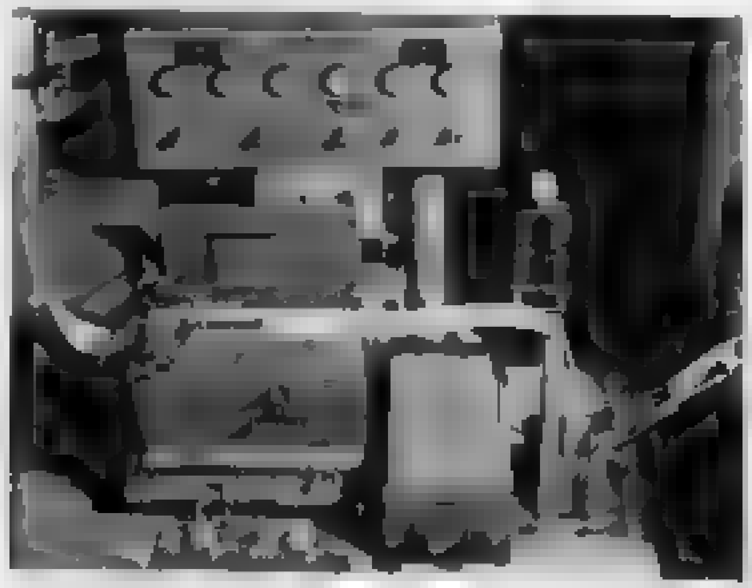

Figure 8. An intra-office tape transmitter

in some cases more) jacks are provided for those destinations. Associated with each jack is a designation card, and a neon lamp that glows steadily as a warning to switching clerks when the intra-office circuit connected to that jack is "closed-out", and flickers when special routing instructions are in effect. One multi-conductor plug and cord, connected to an intra-office transmitter, is mounted in the shelf of a turret for each line receiving position associated with that turret. Therefore, four or eight such cords and plugs are associated with each turret.

The printed-perforated tape between the line printer-perforator and intra-office transmitter passes over the top of a tape neck consisting of a rectangular shaped metal tube. When the line printer-perforator is receiving, the tape loop descends into the metal tube and feeds into a tape accumulator that is mounted under the bottom shelf. The incoming tape, merely by the force of gravity, folds back and forth across the width of the accumulator. When the intra-office transmitter is sending, it draws the bottom fold of tape from the accumulator and yet at the same time incoming tape from the printer-perforator will continue to feed correctly into the accumulator The front and back sides of tape accumulators are made of glass. thus enabling a supervisory check to be made from the switching aisle on the amount of unswitched tape. The "sent" tape flows into a chute after passing through the transmitter, and feeds into a tape bin built into the bottom part of the table

Line Sending Position

The principal items of equipment at a line sending position comprise the intra-office reperforator (Figure 9); the tape accumulator; the line tape transmitter; a distributor (when the position is used for sending to a teleprinter line circuit), the impulse unit, the automatic numbering machine; and the signal lamps, push-buttons and toggle switches which serve various supervisory and trouble-warning functions

The line sending positions are also double-decked. The sending tables, Figure 6, have a shelf at the top on which is mounted some of the equipment associated with the sending positions on the two lower shelves. A row of sending tables is installed on each side of an aisle, each row of tables facing into the aisle No manual attention other than supervisory is required in these aisles. The relays, resistors, connecting blocks and as-

sociated equipment required in circuit arrangements for the sending position apparatus are mounted on the rear of the sending tables, and a small aisle is provided behind each row of tables for testing, regulating and maintenance purposes.

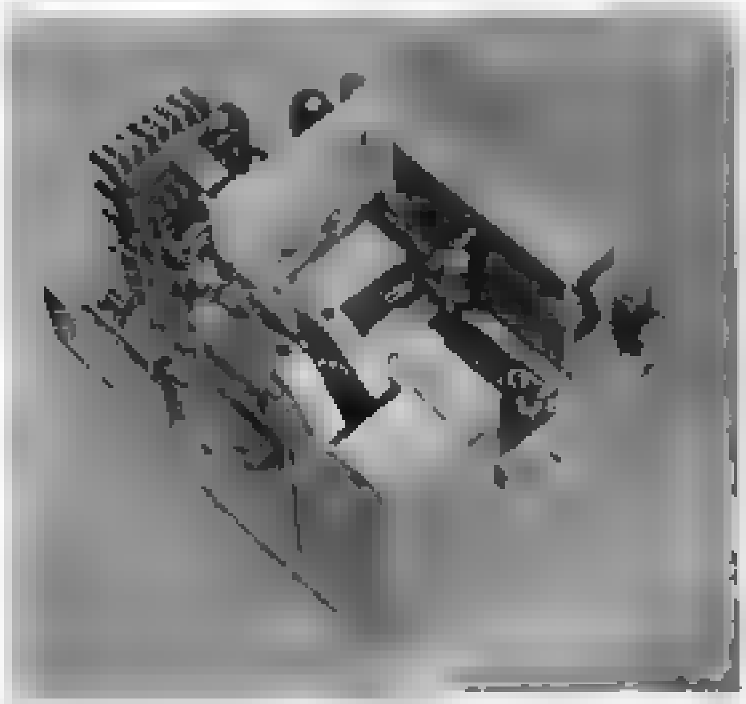

Figure 9. An intra-office reperforator

Tape necks and accumulators similar to those on receiving positions are provided for mechanically protecting the "unsent" tapes between the intra-office reperforators and line tape transmitters. Also, the tape chutes and tape bins are provided for storing the "sent" tape.

Intra-office Switching

The fundamental requirements of intra-office facilities can best be explained by describing the switching and transmission of a message from a line receiving position to a line sending position. Each message received at a receiving position has a prefix consisting of the call letters of the office or position that sent the message into the switching unit; the channel designation, if that line circuit or position has two or more channels (i.e., circuits) into the switching unit; and the sequence number of the message. Also, each message is terminated with two "periods", which are used as an "end of message" signal.

Preparatory to switching a message, the switching clerk checks the sequence number and reads the address of destination as recorded on the receiving position printer-perforator tape. She marks off the sequence number on the number sheet used for that circuit, and also endorses, alongside the number, the call letters of the circuit to which the message will be switched. She then inserts the plug of the intra-office transmitter into the proper jack in the switching turret. Normally, that completes all of her work in connection with any one message. From then on, the operation is automatic.

Inserting the plug into the jack does not immediately connect the intra-office transmitter to the intra-office circuit. It will be noted that each intra-office reperforator circuit is multipled to jacks in all of the turrets in an office. At any given moment two or more transmitters at various turrets may be plugged up to the same intra-office circuit and it is evident that only one should send at a time.

A "transmitter allotter" is provided for the whole switching unit and periodically, every few seconds, it tests one at a time each plugged-up intra-office transmitter circuit in order to determine if the intra-office circuit for which the transmitter is waiting, is busy or idle. If it tests "busy", the plugged up transmitter continues to wait its turn. When it tests "idle", the transmitter seizes the intra-office circuit and immediately "busies" it to any other plugged-up transmitters.

Upon this seizure, the "automatic numbering machine" on the sending position functions to send into the intra-office reperforator the call letters of the area center office, the channel designation, and the outgoing circuit sequence number for that message. At the completion of the operation of the automatic numbering machine, the intra-office transmitter functions to send into the intra-office reperforator the message from the receiving position. When the two consecutive periods at the end of a message are transmitted over an intra-office circuit, they are detected by "code reading" devices and immediately the transmitter is stopped and electrically disconnected from the intra-office circuit. A "disconnect" lamp, associated with the cord and plug at the

jack turret, lights and this indicates to the switching clerk that transmission of that message has been completed and she can proceed to switch the succeeding message.

A fraction of a second after the transmitter is electrically disconnected from the intra-office circuit, that intra-office circuit ceases to be "busy" even though the switching clerk does not immediately remove the transmitter plug from the turret jack. If one or more transmitters are plugged up and waiting for a connection to that intra-office circuit, one of them, through operation of the transmitter allotter, will seize the intra-office circuit and immediately "busy" it to any other transmitters that may be waiting for a connection.

In succeeding articles, the functioning of the intra-office equipment and circuits will be discussed in greater detail. Also later improvements as designed for Philadelphia, Cincinnati, and subsequent installations will be described.

THE AUTHOR: R. F. BLANCHARD has been continuously associated with the Western Union since 1915, holding various positions in Gulf Division offices from Morse operator to Traffic Manager at New Orleans, a position which he held from 1923 to 1928. Early in 1928, he was transferred to the Traffic Engineer's office in New York, and in 1929 was made Assistant Traffic Engineer. He remained in that assignment until June, 1945, when he was appointed New Methods Engineer; in 1946 he became Systems Engineer. By reason of his wide background of traffic operating experience, Mr. Blanchard has been able to make many contributions to the devolpment of new telegraph systems and the improvement of existing systems, with special emphasis on the operating functions thereof. One of his most important assignments was the development of the reperforator switching systems described in these articles, of which he is co-inventor with W. B. Blanton and H. L. Browne (retired).

THE AUTHOR: W. B. BLANTON, Assistant to the Equipment Research Engineer, joined that division immediately after graduating from Virginia Polytechnic Institute in 1922. He has been active in the development and engineering of circuits and equipment for manual, semi-automatic and automatic switching systems that handle telegraphic communications by automatic printer, reperforator and facsimile methods. Mr. Blanton is co-inventor, with R. F. Blanchard and H. L. Browne (retired), of the reperforator switching systems described in these articles.

Some Modern Techniques in Ocean Cable Telegraphy

C. H. CRAMER

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The state of the art in ocean cable telegraphy has been recorded at intervals in the literature of the A.I.E.E. and elsewhere through the early nineteen thirties.[1,2] It is the purpose of this paper to give an account of some of the more recent developments which have been devoted almost exclusively to the improvement of transmission in one of the oldest of the electric signal mediums, the nonloaded submarine telegraph cable.

The limitations of the earliest methods of cable operation were largely determined by the available operating equipment. The receiving instrument first used on the transatlantic cables was the mirror galvanometer, a moving-coil instrument. By reason of its sensitivity and favorable signal-shaping characteristics, the moving-coil type of receiving equipment remained in a dominant position in nonloaded cable operation until relatively recent years. The mirror galvanometer was followed by the siphon recorder which provided a permanent record of the received signals. In turn the recorder was supplmented by magnifiers of various types which amplified the received signals before passing them to the recorder; and by the sensitive cable relays such as the drum relay and the gold wire relay which made possible the abandonment of manual relay operation at repeater stations. All of these instruments were of the moving-coil type. Application of these developments and the regenerative repeaters which followed, extending over the years to the period immediately after World War I, brought about substantial increases in signaling speeds. Recorder operation was still universal, requiring manual transcription of messages from the recorder tape at the receiving terminal.

The success of printing telegraph systems in land-line operation had engaged the attention of cable engineers but trial printer operation on cables, while showing promise, indicated generally the necessity for improved signal transmission before the automatic system could be entirely satisfactory.

Because of the fragility of the moving-coil equipment and the gain limitations of the magnifiers, the potentialities of the vacuum tube in ocean cable telegraphy were recognized early in the development of the electronic art. However, the efforts of 1918-19 toward application of vacuum-tube signal-shaping amplifiers did not produce performance justifying the replacement of magnifiers. The principal reasons for this result were the high disturbance levels generally existent on duplexed nonloaded cables at that time, comprising natural or static interference and duplex unbalance; and the lack of electric networks with shaping and discrimination characteristics better than or even equal to the characteristics of the mechanically-tuned moving coil. Certain practical aspects of the problem also then presented difficulties which subsequently disappeared when improved magnetic materials and electronic components became available.

The continuously-loaded telegraph cable with its promise of considerably higher signaling speeds, which became practical with the invention of permalloy, emphasized the limitations of recorder operation and electromechanical terminal equipment. Necessity thus brought about the concurrent development of a signal-shaping amplifier and a multiplex printer system suitable for high-speed loaded-cable operation. The laying of the first loaded

cable in 1924 between New York and Horta, Azores Islands, and its immediate success are a matter of communications history.[3] The amplifiers and other terminal and repeater equipment[4,5] which formed an important part of that project contributed in no small degree to the overall success of the undertaking. The several later loaded cables were provided with amplifiers of essentially the same design. Most of these amplifiers are still in operation with a continuous record of excellent service. It may well be said that the loaded-cable circuits established a new high standard in reliability, continuity and quality of day-to-day cable operation.

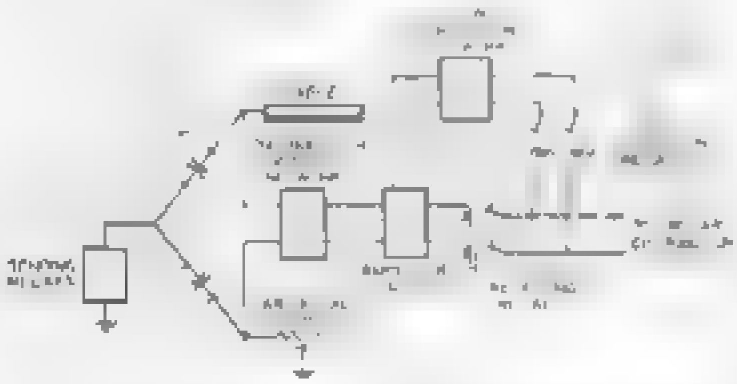

Figure 1. Typical application of signal-shaping amplifier on duplexed nonloaded cable

Following the period of preoccupation with loaded-cable developments and as the success of the new operating methods and equipment became evident, efforts toward improvements in the operation of the nonloaded cables were renewed. The end results of these developments, which may now be regarded as substantially completed, have been successfully applied to a considerable extent in the North Atlantic cable system of the Western Union Telegraph Company. Installations were intensified during the war, in the course of which the developments were made available to the Commercial Cable Company and were utilized in the rehabilitation and extension of the cable system of the Alaska Communication System.

The program has included conversion from cable code recorder operation to 5-unit code printer operation; the replacement of magnifiers with vacuum-tube signal-shaping amplifiers, which also makes possible the use of sturdy land-line type polar relays instead of the mechanically-delicate cable relays; and improvements in duplex artificial line networks and in the technique of balancing. The advantages of more completely automatic operation have thus been made available and at the same time circuit speeds have been increased and circuit and equipment maintenance at the cable stations have been reduced

The Printer System

In view of the high capital cost of the long nonloaded ocean cable and its relatively low signaling speed, the message output of the circuit is a matter of great importance, and thus it is ordinarily essential to use a signaling code with a minimum number of time units per character. For this reason much work has been done on cable printer systems based on various nonuniform codes which average fewer units per character than the Baudot 5-unit uniform code. These systems[6,7] have been tried experimentally and some have had practical application. However, early experiments with printer operation on Western Union cables, confirmed by experience with the loaded-cable circuits, favored the adoption of the 5-unit code with a method of transmission, used also on the loaded cables, which effectively overcomes the relative inefficiency of the code.

The printer system which has been standardized for nonloaded cables does not differ fundamentally from the loaded-cable system but it resembles the land-line multiplex more closely. It utilizes land-line types of transmitters, rotary distributors, synchronizing mechanisms, and printers, thus gaining the advantages of uniformity It differs in two respects from normal land-line practice. It is applied to single-channel as well as to multi-channel operation, whereas the land-line system employs start-stop 7-unit code printers for single-channel applications. Secondly, on long cables the printer signals are transmitted at a speed such that pulses of unit or dot length are received at very small amplitude and may be regarded as completely missing. The receiving networks are adjusted to respond to signals two or

more units long and thus, for purposes of signal reception, the fundamental received frequency is one-half the transmitted-dot frequency. The receiving relay operates as a 3-position relay and remains at the zero position for dot signals. The dots are reinserted synchronously by the receiving rotary distributor.

It might appear at first glance that the attenuated-dot method of transmission would double the cable output as compared with normal multiplex transmission in which all signal elements are received at full amplitude. That must be regarded as a limit which may be approached but cannot be fully realized, because with attenuated-dot transmission the received signals are more susceptible to interference and somewhat more difficult to shape. This device does permit a substantial increase in the letters-per-minute circuit speed, amounting to about 80 per cent over that possible with normal transmission, and thus in effect it shortens the code.

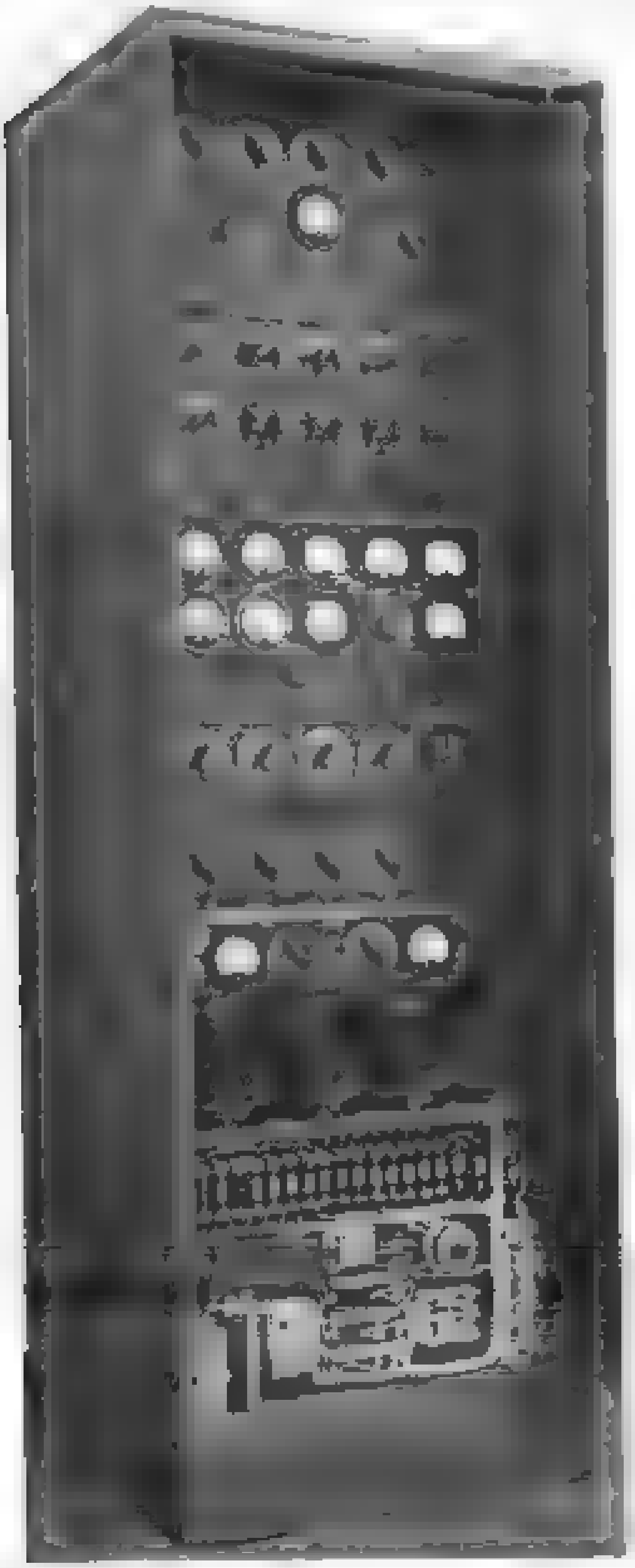

Figure 2. Signal-shaping amplifier for long nonloaded cables

The cable printer system has all the elements of flexibility of the land-line multiplex; that is, individual channels may be terminated, extended or combined with other channels as required to meet traffic conditions and the transmission speeds of the available circuits. Varioplex methods may be applied to obtain subchannels for use as direct point-to-point or customer-to-customer circuits where the full capacity of a channel is not required.

Signal-Shaping Amplifier for Long Nonloaded Cables

The requirements of a signal-shaping amplifier which will permit satisfactory printer operation on long nonloaded cables at the highest practicable speeds are severe. The more important of these are:

1. A higher standard of accuracy is necessary than for recorder operation, in which manual transcription of received signals affords the opportunity to correct transmission errors. A higher standard of continuity and reliability of operation is also now required, determined in part inherently by automatic operation and in part by various present-day competitive and economic conditions. Amplifiers and other operating equipment should thus require a minimum of skilled attention.

2. In transmission, signals are subjected to heavy distortion resulting from unequal attenuation and phase shifting of their component frequencies. At present operating speeds, the attenuation of the higher frequency components of a signal pulse as compared with the lower-frequency components differs as much as 11.5 napiers (100 decibels). The signal-shaping network must equalize

or restore these components to an approximation of the original amplitude and phase relationships.

3. To reduce susceptibility to interference to a minimum, the shaping network must pass only the narrowest band of frequencies consistent with a satisfactorily low degree of characteristic distortion. The network must cut off somewhat sharply above the band to discriminate against extraneous interference and duplex unbalance voltages. It must also reject direct currents as well as alternating currents of near-zero frequency to discriminate effectively against earth currents, particularly during the abnormal conditions accompanying magnetic storms.

4. In the case of duplex-operated cables—and almost all nonloaded cables are at least held available for duplex operation — the shaping network should be electrically symmetrical with respect to the duplex bridge, or electrically isolated from it so that the network and the amplifier do not of themselves contribute to the duplex unbalance. Signal-shaping amplifiers meeting this requirement, including spare equipments, may be assigned interchangeably to various cable circuits without requiring readjustment of balances.

5. The network elements must be provided with a considerable degree of adjustability Approximate network constants may be calculated but the optimum values must be determined for each cable by manual adjustment.

6. The amplifier should be provided with sufficient gain and output to operate rugged polar relays of the general type standard in land-line telegraphy

The signal-shaping amplifier which is now regarded as standard for long nonloaded cables meets the requirements detailed above and may be viewed, at least for the present, as a satisfactory conclusion of several years of laboratory development and field operating experience A standard installation, Figures 1 and 2, includes a primary or pre-amplifier shaping network, an amplifier unit, receiving relays, and a secondary shaping or local correction network which supplies low-frequency components of the signals rejected by the pre-amplifier network

The pre-amplifier network, Figure 3, when correctly adjusted, passes a band which includes all of the higher-frequency components of the signals required for good signal shape, properly proportioned and phased Frequencies below the fundamental received frequency are heavily attenuated, with almost complete rejection in the range of earth current disturbances. The first branch of the network, symmetrically arranged and directly

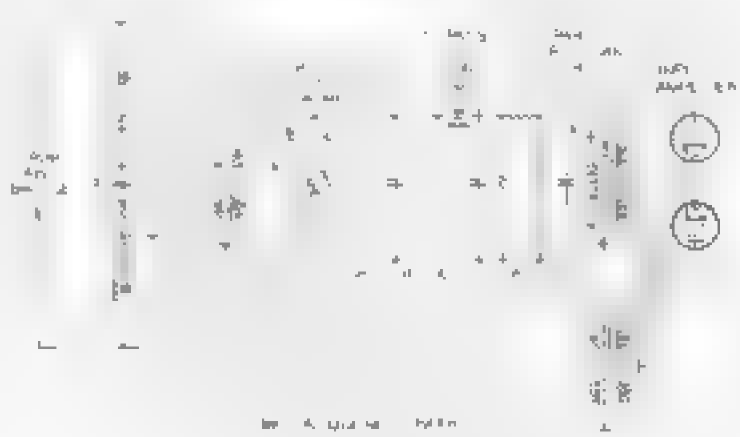

Figure 3. Pre-amplifier signal-shaping network

connected across the duplex bridge, together with the effective capacitance of the cable circuit, is tuned to about 1.5 times the received frequency. The following elements of the network are isolated from the first branch by shielded transformers so that the effect on duplex balance is negligible whatever their arrangement. In one path the lower frequency components are passed to the amplifier input with little or no further shaping Higher-frequency components are further shaped in the second path which includes a bridge-type phase-adjusting network, a low-pass filter section for additional suppression above the required signal band, a parallel resonant circuit tuned to 1.5 times the received signal frequency, and suitable resistance controls. The two paths are again combined at the input to the amplifier. This network provides additional flexibility and refinement of control over that obtained with networks in which shaping of all components is accomplished in a single path. By use of the phase-adjustment network, the required steepness of wave front is secured with less of the higher-frequency components, thus narrowing the band at the upper end and discriminating more effectively against interference. The network fre-

quency response given in Figure 4, which includes the characteristics of the amplifier as described below, is typical of those obtained in actual operation.

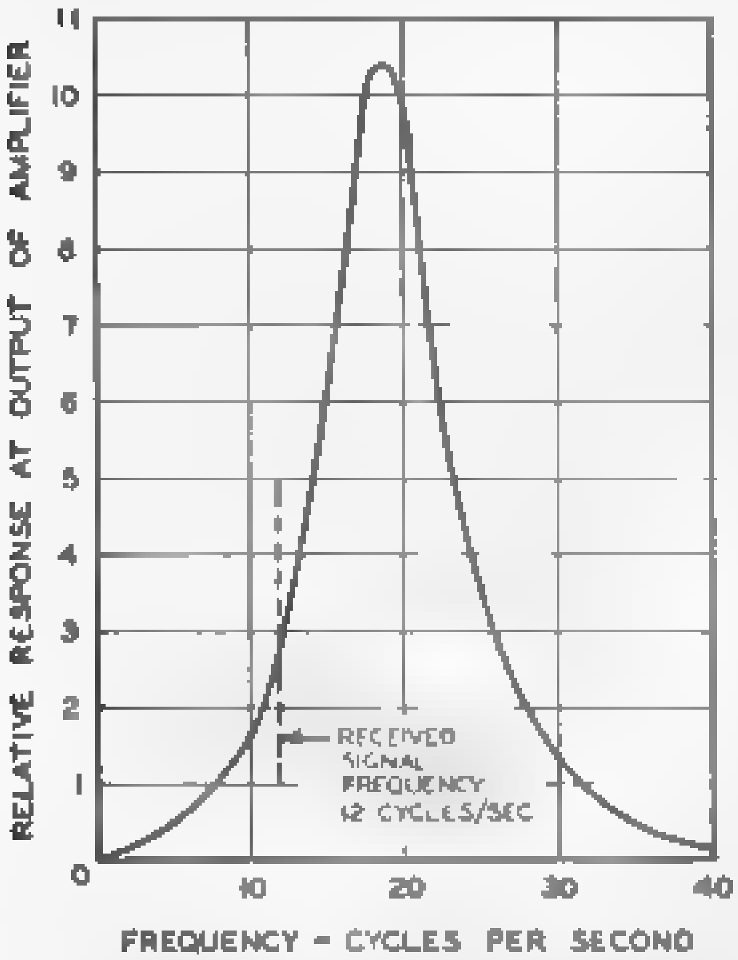

Figure 4. Frequency characteristic of signal-shaping amplifier

Printer operation attenuated-dot transmission, 575 letters per minute (dot frequency, 24 cycles per second)

The three-stage resistance capacitance-coupled amplifier is of a push-pull type with two stages of voltage amplification. The time constant of the interstage coupling is such as to suppress frequencies below those transmitted by the shaping network. This effectively eliminates disturbances or sways which might otherwise result from power supply variations. The maximum voltage gain of the amplifier is about 83 decibles. The available overall gain for the higher-frequency components, including the input transformer, is about 103 decibels. This provides a reasonable margin above the maximum gain likely to be required for the most severe conditions of application. The output of the amplifier is adequate for the operation of modern land-line type polar relays. Following usual cable practice, the normal receiving relay circuit comprises a pair of standard 2-position relays functioning together as a 3-position relay. This circuit is readily converted for optimum reception of 2-current signals.

A long square-top signal transmitted from the far end of the cable is reproduced at the receiving end as shown in Figure 5. The signal as it appears at the output of the pre-amplifier network, 5C, rises to maximum amplitude in the time of the shortest received signal and then decays to zero. At this point signals of the fundamental received frequency are fully shaped and suitable for operation of the receiving relays, but longer signals would be badly distorted because of the deficiency of low-frequency components. These components are restored by the local correction network, Figure 1, under control of the receiving relays. The shaped local correction voltage, 5*D*, is added to the received signal in the grid circuit of the output stage resulting in the fully-shaped signal, 5*E*, which, if required, will hold at constant amplitude indefinitely.

The general method of shaping involving local correction, while considerably

Figure 5. Received signal resulting from transmission of long signal

A—Component through high-frequency path of pre-amplifier network

B—Component through low-frequency path of pre-amplifier network

C—A+B

D—Component supplied by local correction network

E—Complete signal C+D

F Fundamental received frequency

refined in the present application, is not new. It was normally utilized in some degree in the magnifier shaping systems. It differs from the method employed in the loaded-cable amplifiers in which essentially all shaping is accomplished in preamplifier and interstage networks with, however, some deficiency in the very-low-frequency components. The advantages over the latter method include, in addition to the relative immunity from low-frequency disturbances mentioned previously:

1. Simplification of amplifier design and increased amplifier stability, since the amplifier is not required to pass the lowest signal frequencies.

2. The received signals are not subject to "wandering zero", the slow transient resulting from signal combinations in which the polarities are unbalanced.

Duplex Operation

Since duplex operation of nonloaded cables normally affords greater total message capacity, that method is usual unless abnormal transmission and traffic conditions favor one-way operation. With modern amplifiers in use, extraneous interference and duplex unbalance levels determine the top signaling speeds. If unbalance is the principal factor, maximum capacity is obtained with the speeds in the two directions unequal; for example, two printer channels in one direction and a single channel in the opposite direction. Parenthetically, it may be remarked that in addition to the transmission factors, efficient utilization of operating personnel is also a factor in determining channel speeds and maximum circuit capacity. The importance of duplex unbalance as a limiting factor has been reduced in recent years through improvements in artificial line networks and balancing methods.

The Duplex Balance

The basic ocean cable artificial line, Figure 6*A*, has changed little in form since the early days of duplex operation. The lumped series resistance and shunt capacitance elements, simulating the conductor resistance and the capacitance of the cable, have varied somewhat in fineness of subdivision over the years. In some instances greatly increased adjustability has been provided. It has been well established in theory[1] and practice, however, that the very fine subdivisions employed throughout many of the existing artificial lines are unnecessary from the standpoint of balance accuracy. Further, the size of the lumps may be progressively enlarged along the artificial line, since the accuracy with which the cable must be matched decreases as distance (and attenuation) from the head of the artificial line increases. Modern artificial lines of American design follow this pattern and have the advantage of simplified and less costly construction.

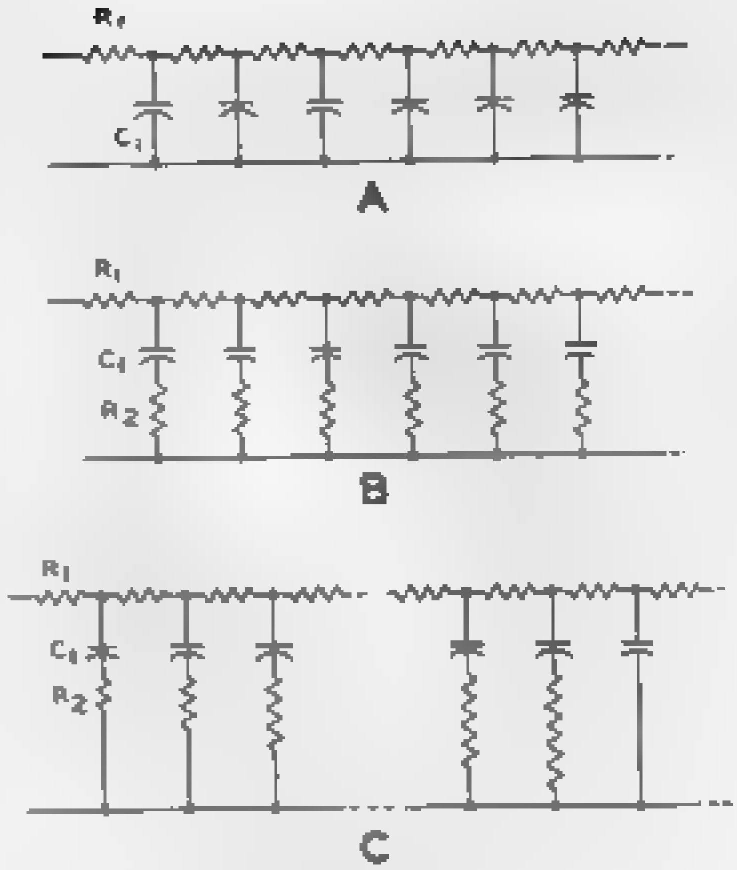

Figure 6. Artificial line networks

A—Basic artificial line

B—With uniform R_2 added to simulate inductance

C—With tapered R_2 to simulate inductance and effective resistance

Although the basic artificial line simulates directly only the d-c resistance and the capacitance of the cable, the circuit parameters include inductance and effective resistance which vary with frequency because of the characteristics of the earth-

return path[8] and are commonly termed the sea-return impedance. These factors, Figure 7, although small and generally of minor effect on signal transmission, are of considerable importance in balancing, particularly in high-accuracy balancing of the near end of the cable. Inductive networks have been added to artificial lines in various forms[9, 10] and while theoretically an accurate simulation of the sea-return impedance can thus be obtained, it is difficult practically to provide inductors or inductive networks which have the required characteristics and ease of manipulation. Artificial line modifications of that type have not proved to be a satisfactory method for obtaining balances of the order of accuracy now demanded.

Simulation of Sea-Return Impedance

Milnor has shown[1] that in a uniform network of the form illustrated in Figure 6B, the resistances R_2 in series with the capacitors provide a match of the cable inductance L if

$$R_2 = \frac{L}{R_1 C_1} + \frac{R_1}{4} \qquad (1)$$

and R_1, C_1 are equal to the corresponding cable parameters. The balance is correct for all frequencies if L is constant. Actually the inductance varies with frequency as indicated in Figure 7. While for this reason the uniform network is not a complete answer, it can be applied to a very limited extent at the head of the artificial line with some beneficial results at the frequencies requiring the greatest accuracy of balance. Another factor which limits the use of the network is that its propagation constant differs substantially from that of the cable and hence affects the balance of the following sections of artificial line, particularly as the cable is commonly not uniform as to core size, armoring, and so forth.

More recently it has been found that if R_2 is tapered as in Figure 6C, the sea-return impedance is simulated over a relatively wide band of frequencies, and further that there is no important change in the propagation constant of the section of artificial line to which it is applied. The taper which has provided the best results experimentally may be defined by the empirical equation

$$L_1 = K_1 \epsilon^{K_2 d} \qquad (2)$$

in which L_1 is the apparent value of inductance to be balanced, d is the distance from the head of the artificial line (or cable) and K_1, K_2 are constants related to the parameters of the cable. Now, with values of R_2 calculated by substituting L_1 for L in equation 1, a balance of both inductance and effective resistance is obtained. For optimum results the taper should be terminated at a critical distance from the head of the artificial line, dependent also upon the cable parameters. Empirical equations for this relationship may likewise be set up. Experimentally, the point of termination is determined by inserting R_2 section by section until the cumulative added impedance equals the difference in impedance between the cable and the basic artificial line. The section of artificial line thus modified corresponds to the first 100 to 150 nautical miles of cable and the number of resistors added is usually less than ten. For some types of cable it may be advantageous to insert a second taper system to increase the

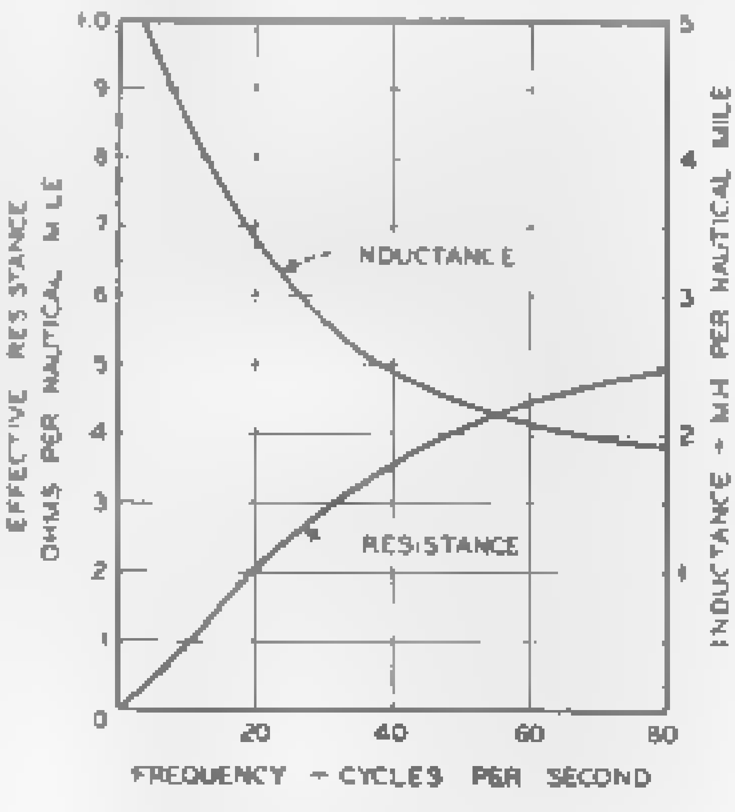

Figure 7. Inductance and effective resistance or sea-return effects of a common type of cable

accuracy of matching at the lower frequencies.

Figure 8 shows comparative residual unbalances with the artificial line set to match only the d-c resistance and the capacitance of the cable, and after the insertion of the tapered resistance. It should be noted that neither of these conditions represents a balance sufficiently accurate for duplex operation. They are instead only foundations upon which the operating balance may be built.

Under the first condition, reduction of the unbalance is accomplished by a series of time-consuming cut-and-try compromise adjustments which must provide a sea-return impedance balance as well as refinement of the resistance-capacitance balance. The necessary compromises frequently result in a considerable distortion of the resistance-capacitance ratio in some sections of the artificial line.

In the second case, where the initial balance includes a simulation of the sea-return impedance approximating in accuracy that of the other components, refinement of the balance is less difficult, requires less time and a final balance of greater accuracy can be obtained.

Frequency Analysis of Unbalance and Application of Resonant Corrective Networks

The conventional method of balancing involves transmission of slow reversals and observation of the residual unbalance transient by oscillograph or ink recorder while adjusting the artificial line. In the final stages of the adjustment, unbalance resulting from transmission of signals at operating speeds is also observed. Adjustment in this manner of the basic artificial line or any of its modifications eventually reaches a point where further reduction of the unbalance becomes impracticable. The limit occurs on specific cables at different levels of balance. The limit may be determined by one or more of such factors as inadequacy of artificial line, masking effect of extraneous interference, inability of the technician, however skilled, to make further beneficial adjustments by cut-and-try methods or by mental analysis of the unbalance transient.

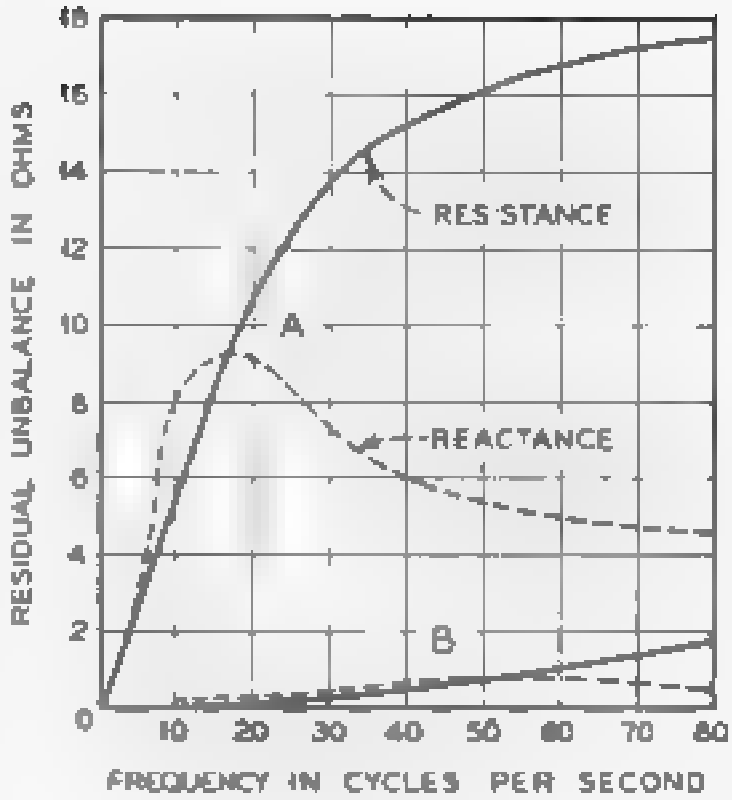

Figure 8. Frequency characteristic of unbalance

A—Basic artificial line set to simulate d-c resistance and capacitance of cable

B—With tapered resistance R_s added (Figure 6C)

These barriers have been lowered by a new approach to the problem in which corrective resonant networks are applied, each supplying an impedance which can be effectively controlled as to magnitude and width of frequency band. The networks are designed in accordance with a frequency characteristic of the residual unbalance. Methods involving frequency analyses of the residual unbalance have been used[11] in the step-by-step development of synthetic balancing networks, with the object of avoiding the relatively expensive conventional artificial line. In the method here presented the artificial line is retained and the resonant networks are applied to improve existing balances.

The frequency characteristic which is the basis of the method may be obtained by a mechanical harmonic analysis of an oscillographic record of the unbalance transient, or the effective residual impedance unbalance at the head of the artificial line may be measured directly across the duplex bridge through the important fre-

quency range. The first procedure has the advantage, perhaps useful under special conditions, of permitting the analysis to be carried out at a location away from the cable station. The electrical measurement, which is now used exclusively in practice, requires considerably less time and it is more accurate since extraneous interference is rejected by sharply selective filters.

The preferred network, of the parallel-resonant type, and the manner in which it is inserted in the cable circuit are illustrated in Figure 9. The network consists of a variable air-gap transformer with low-inductance primary and a high-inductance secondary tuned to the desired frequency and suitably damped to obtain the required impedance characteristic. A single network is effective over only a part of the frequency range and for best results several networks may be required, some in series with the artificial line, some in series with the cable, as the artificial line impedance at different frequencies is deficient or excessive. The low-inductance primary, usually from a fraction of a millihenry to several millihenries, and its low d-c resistance are desirable to avoid unwanted effects on signal transmission and balance. The high-inductance secondary permits tuning at the low frequencies involved with practical sizes of capacitors.

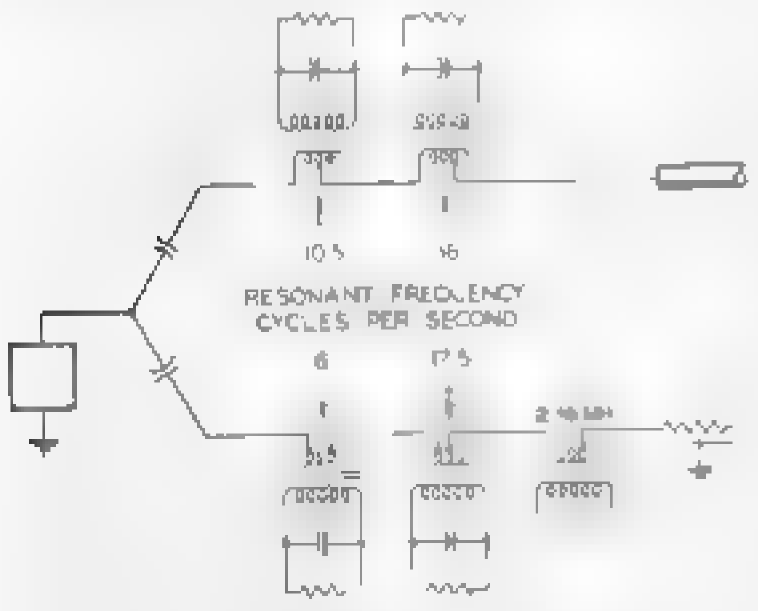

Figure 9. Typical installation of resonant balance networks

Figure 10 shows the frequency characteristics of the unbalance on a typical circuit adjusted for best balance and be-

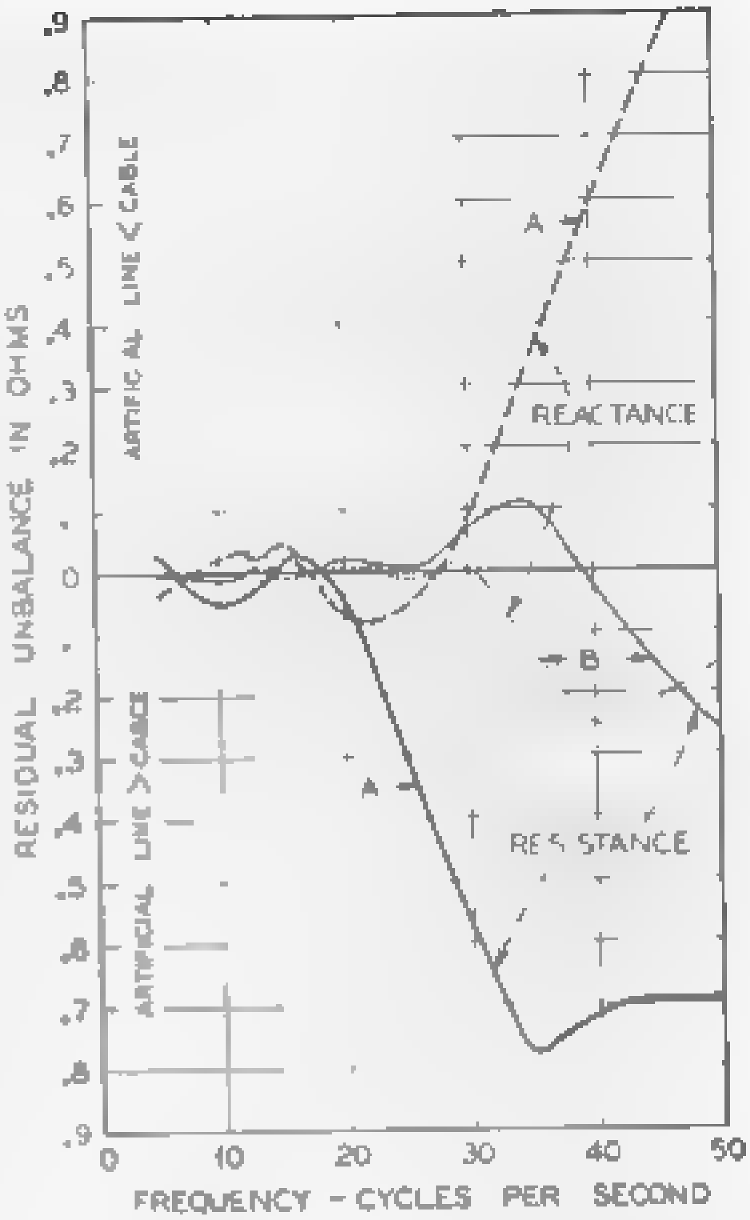

Figure 10. Frequency characteristic of unbalance on a transatlantic cable

A—Before insertion of networks as shown in Figure 9

B—After insertion of networks as shown in Figure 9

fore the application of corrective networks, and the unbalance on the same circuit after the insertion of the networks indicated in Figure 9. It is to be noted that the balance has been improved not only within the most important frequency band but that the greatest reduction has been made at the higher frequencies. The high-frequency unbalance, largely ignored previously and although heavily attenuated by the signal-shaping network, has affected operating balances by reason of its magnitude. The final balance following the insertion of resonant networks is obtained by minor adjustments of the usual artificial line controls. An important further advantage of this method of bal-

ance refinement is that the work may be carried on without disturbing the existing operating balance, so that the circuit may be quickly returned to operation if required. Also the networks can be designed and checked to a large extent independently of the cable circuit and thus without interruption of circuit operation.

While the frequency-analysis technique is essential in the design of resonant balance networks, it has proved to be very valuable in balancing work generally. For example, development of the tapered sea-return impedance correction would have been difficult if not impracticable if the study had been limited to transient effects.

The Cathode Ray Oscilloscope in Balancing

The cathode ray oscilloscope, when provided with the slow sweep necessary for the very low frequencies encountered, has proved to be an important and versatile adjunct in balancing work. Compared with electromechanical types of oscillograph it is more convenient to use and reduces the time required for balancing since the effect of an adjustment can be observed immediately. It is free of the frequency limitations of ink-writing recorders. By use of a retentive-screen tube and superposed traces of the unbalance transient, the effects of interference are more readily discounted. It is particularly suited to observing abnormal unbalance effects such as polarity distortion in which transmitted pulses of opposite polarity produce unlike unbalance transients.

Interference

Crossfire between cables is not unusual where two or more cables land at the same point and may of necessity be laid with small separation between cables. Such interference is controlled readily by use of simple corrective networks at the cable stations. The most difficult crossfire condition results when two cables, landing at different points, have been laid closely parallel or with a small-angle crossing some distance from the landing points. In such instances, correction requires a more complex network including a delay network and a wire connection between the cable stations. One correction of this type has been applied effectively in which the cable stations are located about 30 miles apart.

With the means now available for improved balances and for correction of crossfire, extraneous interference, mostly of natural origin, becomes, in general, the most important factor preventing further increases in speed. Natural interference is picked up in the shallow-water end section of cable and its magnitude, depending upon the depths and distances encountered, varies widely from cable to cable. Receiving earths of the nonloaded cables are generally located at distances up to several miles from shore. The cable conductor and the earth connection are carried to the earthing point in twin-core cable which provides a considerable reduction of the interference within that section. Reduction of the existing levels of interference could obviously be accomplished by extending the twin-core sections, but that, unfortunately, is costly. Some improvement has been obtained by increasing the sending voltages which until recent years were conservatively restricted to about 50 volts. In the Western Union cable system voltages of 90 to 120 are now in common use.

Conclusion

All of the transatlantic nonloaded cables of the Western Union Telegraph Company have been converted from cable code recorder operation to 5-unit code printer operation. The Commercial Cable Company has installed like equipment on two of its transatlantic circuits supplementing an earlier installation of 5-unit code equipment of different design on a third circuit. The advantages of more completely automatic operation, greater flexibility including use of sub-channeling methods such as the varioplex, and uniformity with land-line multiplex printer systems have been obtained, while at the same time the message-handling capacity of the cables has been generally increased. Improved signal transmission insuring the

success of the conversion has been obtained through use of vacuum tube amplifiers and improved signal-shaping networks, more accurate duplex balances, and by reduction of crossfire and use of increased sending voltages which provide a better signal-to-interference ratio.

Signal-shaping amplifiers of the type described in this paper are in use on all of the long nonloaded cable sections of Western Union's North Atlantic system and short-cable amplifiers, of which several types are available to meet a range of requirements, are in operation on the short connecting cables of the system. The Commercial Cable Company has amplifiers installed and in course of installation on the long and short cable sections making up four of its transatlantic circuits.

The new resonant-network balancing method has been applied by the Commercial Company to three main circuits involving 14 cable sections. Utilization of the latest balancing methods in the Western Union system has been more gradual because existing balances had been improved by use of modern types of observing instruments in conjunction with conventional balancing procedures, and by application of forerunners of the methods described in this paper. Of greatest technical interest perhaps, are the results obtained with the new methods on the Commercial Company's heavy-core cable laid in 1923 between Canso, Nova Scotia and the Azores. On low-resistance cables sea-return impedance effects become relatively more important, particularly in view of the higher signaling speed. Theoretical indications of difficulty in balancing cable of this type for the expected speed were confirmed in practice. Experience with an inductive balancing network[10] was unsatisfactory and its use had been discontinued. In the course of the present work the balances were refined with resonant networks, supplemented at the Azores end only by an early version of the tapered sea-return impedance correction. As a measure of the improvement obtained, the previous 2-channel recorder speeds of 550 and 575 letters per minute eastward and westward, respectively, were increased initially to 600 letters per minute in each direction and the performance of the circuit was substantially improved. The ultimate speed in printer operation, when 3-channel multiplex equipment is available, is expected to be 750 letters per minute in each direction.

On the duplex-operated nonloaded cables of the Western Union system, the sum of the letters-per-minute speeds in the two directions now averages in printer operation more than 40 per cent above the previous recorder speeds. The average net increase in the message capacity of these cables, taking into account the short cuts, abbreviations, and so forth, commonly practiced in recorder working but not practicable in printer operation, amounts to more than 30 per cent.

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RADIO BEAM TERMINAL
Washington, D. C.

In the dome of this tower, behind the fiber-glass windows, are the directive radiators, receiving collectors and super-high frequency radio equipment of Western Union's Washington radio terminal. This is one corner of the radio beam triangle which will interconnect Washington with Philadelphia, New York and Pittsburgh.

Intermediate frequency and modulating radio equipment is housed in the second floor of the building, along with carrier translating equipment for converting the 150 kc intelligence band into a maximum of 32 voice band circuits. The first floor houses the battery plant, emergency engine driven generator plant, and the heating equipment.

The derived voice bands are extended to the Washington "Traffic" office several miles away on underground cable. In the latter office, each voice band in service will be connected to 16 telegraph carrier channels.

The Application of Western Union Multiplex to Navy Radio

RAY HOOVER

A paper presented before the Midwest General Meeting of the American Institute of
[illegible]

Introduction

Of the many successful accomplishments of the United States Navy, the feat of providing adequate communication facilities for the conduct of a global war ranks high among those tasks acclaimed "well done". Just prior to Pearl Harbor, the problems confronting Naval Communications became more numerous due to rapidly increasing message load to far distant outposts for operational and administrative purposes, coupled with a growing usage of commercial cable and radio systems by other government agencies, notably the State and War Departments. At the time when most of the new Navy equipment was being allocated to the Atlantic area in support of our allies-to-be, there was available for Pacific coverage only one commercial submarine cable between the United States and the Philippine Islands with intermediate stations at Honolulu, Midway and Guam, and a few Navy radio circuits which were single radio-telegraph channels operated manually or semi-automatically with tape transmitters and siphon recorders. Full automatic operation of these channels by teleprinters had not yet become entirely practicable.

With the beginning of hostilities after the Japanese attack on Pearl Harbor, these Pacific facilities immediately became overloaded, and it was only a short time later that the Philippine cable was rendered inoperative by enemy action. The Navy immediately set about increasing the number of radio circuits in operation.

When the allies took the offensive and began to regain bases previously captured by Japan, the message volume rose to even higher levels, and the building of new circuits and modernization of the older systems by the use of printing telegraph equipment could no longer satisfy the new requirements as rapidly as necessary.

During the early part of 1943, the Navy Department asked the Western Union Telegraph Company to assist in expanding message capacity and improving continuity of transmission over the existing Navy radio channels. Captain M. W. Arps, now retired, who was then officer in charge of the Cheltenham Naval Radio Station, was assigned the duty of coordinating the planning and engineering of the project. The scope of the activity and the results achieved by the use of the Western Union multiplex on long Naval Radio circuits are described in the following paragraphs.

The Radio Systems

The history of long-distance short-wave transmission shows that the most useful radio systems fall into two general classes of development. The first of these, intended for radio telephony, comprise the single sideband systems which conserve frequency spectrum and power to the highest degree. The most advanced design provides two telephone channels, one on either side of the carrier frequency, which is not transmitted. The systems of the other group comprising the second class of development are intended for radio telegraphy, and were originally of the keyed continuous-wave type. For many years semi-automatic tape sending and siphon recording on paper tape were used. To overcome the frequent loss of signal caused by selective fading of the single frequency, it became conventional to employ a frequency deviation of about 500 cycles in the carrier frequency in addition to the keying modulation. But when

it became necessary to improve operation by connecting printing telegraph equipment to the terminals, it was found that the presence of echo signals and impulse noise made automatic operation impractical except on the very best circuits. Then followed a period during which terminal signal regeneration and antenna improvements, together with higher power, made possible the use of printers on a few of the better circuits. But these circuits were not dependable to the degree ordinarily experienced with ocean cable transmission. The invention of the error-proof printer, requiring 7 instead of 5 code pulses per letter, removed practically all of the remaining uncertainty,[1] but this required higher keying speeds for the same word speed, and rather complicated translation apparatus if transmission was to be integrated with systems employing seven-unit start-stop transmission, such as the teleprinter. And it should be remembered that space diversity reception was considered necessary to eliminate the effects of signal fading, which required such values of antenna separation that the system could be used only on fixed circuits, and was not suitable for transmission to air and surface ships of the Navy

The remaining significant improvement applied to Navy radio-telegraph circuits during the first years of the war was frequency-shift keying In this system, one frequency is employed for the marking pulses, and another frequency approximately 850 cycles removed is used for the spacing pulses. Frequency-shift keying had been used on wire circuits since 1938.[2] The carrier has substantially constant amplitude, but the instantaneous frequency may vary abruptly or gradually between the two limits. Hence it is a frequency modulation of the carrier frequency by a modulating wave which is obtained from the keying relay, but with a certain amount of shaping applied to the normally square signaling wave to reduce the band-width required for transmission. This type of transmission is distinguished from two-tone transmission in that a frequency-modulation detector and limiters are employed to convert the received signals into direct currents which operate the receiving relay.[3] The limiters act as fast automatic level controls which help overcome rapid fading without danger of raising the noise to the level of the signal, since the signal is transmitted constantly instead of intermittently. The system is relatively insensitive to impulse noise, and remains free of bias distortion resulting from rapid level changes. However, it requires approximately the same band width as the single sideband telephone system previously mentioned, as contrasted with the narrow band originally needed for a continuous wave system.

It should be mentioned that the radio-telephone systems were more easily multiplexed, that is, made to carry several telegraph channels, by frequency division methods,[4] whereas the radio-telegraph circuits already consisted of single telegraph channels which could be multiplexed only by time-division methods. The former system suffered the disadvantage that the available power of the transmitter had to be divided between several frequency bands, one for each telegraph channel, and the further disadvantage that two or more tone frequencies had to be used for each marking or spacing signal to avoid the effect of selective fading Therefore, it was wise that the Navy decided to adopt frequency-shift keying which resulted in the best signal quality available, and then found a means to speed up the message flow over this system

Initial Tests

When work was first started on the problem, a high-speed teleprinter which was under test in Western Union's New York Laboratories was considered It was thought that this machine would suffice for the interim of further research One model geared to operate at 107 words per minute was dispatched to Cheltenham where it was placed under test. A distributor-transmitter making use of a prepared tape was used to originate the signals, and circuits were set up on radio channels between Cheltenham and distant points such as Honolulu and Balboa, where the signals were repeatered back to the printer. These tests were satisfactory, but

since Western Union was not tooled for production of these printers, and only a few laboratory models were immediately available, it was necessary to look for other ways for a final solution. Tests had already been started on the use of multiplex equipment and it developed that immediate delivery could be made if standard equipment could be used. A test using a standard Western Union four-channel multiplex was made over a Navy radio circuit between Cheltenham and Honolulu with the signals repeatered back to Cheltenham from Honolulu, and while the actual printing test was of short duration, it was demonstrated that the use of a four-channel multiplex was within the realm of possibilities. To further test the system for printing margins, a circuit was set up from the New York Laboratories over a wide-band carrier channel to Washington and a Navy Tone Channel to Cheltenham, using the same radio system as previously used to and from Honolulu. The signals were retransmitted to New York over Navy Tone and Carrier Channels. These tests enabled us to determine the weak points in the system, and also proved beyond all reasons for doubt that the application of multiplex to radio could become a reality with a minimum amount of effort. During these tests Naval observers were picking out flaws in the radio equipment and, as a result, they made recommendations on desirable changes in the standard Navy radio equipment. It was also suggested that consideration be given to the use of seven-unit start-stop teleprinters, for recording the signals at the receiving side of the multiplex system, instead of the conventional five-unit multiplex printer. This would permit the extension or repeatering of a single channel into another radio link or to some remotely located outpost without the necessity of manual handling. It was also considered desirable to use a recently developed fork corrector instead of the conventional mechanical or motor type of corrector for maintaining the proper phase relation between the sending and receiving multiplex terminal sets. Both the Navy Department and Western Union set out to accomplish the changes agreed upon, and in April, 1944, the first sets were installed in Washington and Honolulu. After the initial tests, that required less than a week, these two offices were interchanging messages at the rate of 60 words per minute per channel in each direction, which is 240 words per minute over four multiplex channels working on a single Navy radio channel. Other installations followed in rapid succession. Practically all Naval bases of operation in the Pacific were ultimately equipped with this type of operation.

The Baudot and International Morse Codes

As a character of the Baudot code may have successive signal impulses of the opposite polarity, the maximum number of cycles required to transmit the five impulses of a single character will be 2.5. All characters or functions of the Baudot code are transmitted in equal lengths of time, as distinguished from the International Morse code which requires differing lengths of time for the transmission of different characters. Operating speeds of telegraph circuits are usually stated in terms of words per minute transmitted, the average length of the word being assumed as five letters and a space. In the Baudot code, therefore, 30 signal impulses must be transmitted to convey any such word to the distant point. In the International Morse code varying numbers of such impulses are required, depending on the word considered. A dot requires the time of two impulses; a dash four; the interval between letters two; and between words two additional. It has been determined that a word representative of the average of five-letter words is "Paris" and the time of 48 signal impulses is required to transmit it in Morse. The four-channel multiplex system described in this paper and using Baudot code transmits 240 words per minute. From the above ratio of length of codes, 30 48, it will be seen that the time length of the shortest signal impulse at this rate of transmission will be equivalent to the time length of the shortest signal impulse of the International Morse code when transmitted at the rate

of 150 words per minute. Or if stated in another manner, the highest fundamental signaling frequency used in the transmission of signals by a four-channel multiplex operating at sixty words per minute per channel is sixty cycles. The highest fundamental signaling frequency used in the transmission of 150 words per minute International Morse code signals is also sixty cycles per second. The multiplex system, when sending a steady train of signal impulses which are successively marking and spacing will, therefore, produce the same signal that will result from the transmission of a succession of Boehme dots at the rate of 150 words per minute. The multiplex as applied to land line circuits,[5] has been in use by Western Union since 1913

Synchronization Between Receiving and Sending Terminals

It will be recalled that in order to maintain the brushes at the sending and receiving ends of the system in synchronism and in phase with each other, each of the brush arms on the distributor is driven by an impulse motor, this motor being controlled by a tuning fork which is equipped with suitable contacts. When the system is first put into operation, both the sending and receiving tuning forks are set at as nearly as possible the same vibrating speed. Even with highly constant speed forks, some correction is necessary to maintain the position of the receiving brush arm with respect to the sending brush arm. A corrector system at the receiving terminal makes use of the incoming intelligence signal from the sending terminal to indicate whether the receiving brushes are advanced or retarded with respect to the position of the sending brushes. This determination is made by using the points at which signal reversals occur. These signals are used to control the grid of a vacuum tube which in turn, through its associated control circuits, varies the current through a damping coil applied to the tuning fork to either slow down or speed up the vibrations of its tines.

Theory of the Multiplex as Applied to the Navy Radio Systems

To make the multiplex system applicable to the Navy's communications system, a start-stop seven-unit teleprinter was substituted for the conventional five-unit multiplex printer. This substitution eliminated the necessity of manual retransmission from a multiplex radio circuit to a teleprinter radio circuit, or a land-line circuit. Because of the fundamental difference in operation of a multiplex system and a start-stop system, it was necessary to provide means on the receiving terminal distributor for converting the signals to the desired form. Figure 1 shows

Figure 1. Elementary theory of a 7-unit start-stop telegraph system

in theory a start-stop system. The distributors differ from those of a multiplex system in that the brush arms are driven by an electric motor through a friction clutch. Both brush arms are driven at a constant speed by synchronous or accurately governed motors. The receiving arm is slightly faster than the sending arm, so the start signal at the sending distributor will cause the brushes to leave the rest segment on the receiving distributor at the proper time, thereby maintaining the phase relation between the two stations. This system[6] is commonly called a start-stop seven-unit system, five units being used for transmitting intelligence, and the other two for synchronizing purposes. The segment positions on the receiving face plate are such that the brushes rotate simultaneously over similarly numbered segments at the two terminals. Each of the individual selecting circuits at the receiving terminals has a marking or spacing signal applied to it in

accordance with the positions of the keys at the sending end. In the multiplex system it was not possible to initiate the start and rest pulses at the sending end, so to make it adaptable to the Navy's needs, it was necessary that a storage means be provided at the receiving terminal in order that these two pulses could be inserted locally after the five intelligence pulses had been received.

Assuming that the signals originate in a tape transmitter at the sending end in the multiplex system, Figure 2 shows the receiving channel theory as finally developed for the Navy Department. Associated with each of the four receiving channels were five storage relays, five 6V6 vacuum tubes, five neon lamps, and a single 2050 vacuum tube. Common to all four multiplex channels were a polar line relay, a selector relay and a second polar relay associated with a 6V6 tube and loud speaker. The polar line relay is used to receive the signals from the radio circuit. Applied to its spacing and marking contacts are positive and negative battery respectively. This relay, as it operates, applies a signal to the corrector relay, Figure 3, and also to a coil of the selector relay, Figure 2. The ground connection through a condenser and resistor to the line relay tongue merely acts as a spark protection circuit. The selector relay, which has three of its coils connected in series to the tongue of the line relay, together with the receiving rings on the distributors, make up a terminal regeneration circuit. The purpose of this circuit is to regenerate the received signal so the signal which is finally applied to the grids of the selector tubes will be free of distortion. There is a limit, of course, to the distortion which may be present in the received signal and yet cause the selector relay to operate in accordance with the signal as transmitted. The terminal regeneration circuit does insure, however, that the grids of the selector tubes will have applied to them a definite solid signal, even though the received signal has been so distorted that it has failed to operate the line relay in accordance with the transmitted signal. As the receiving ring brushes pass over the segments associated with the 6V6 tubes, connection is made from the tongue of the selector

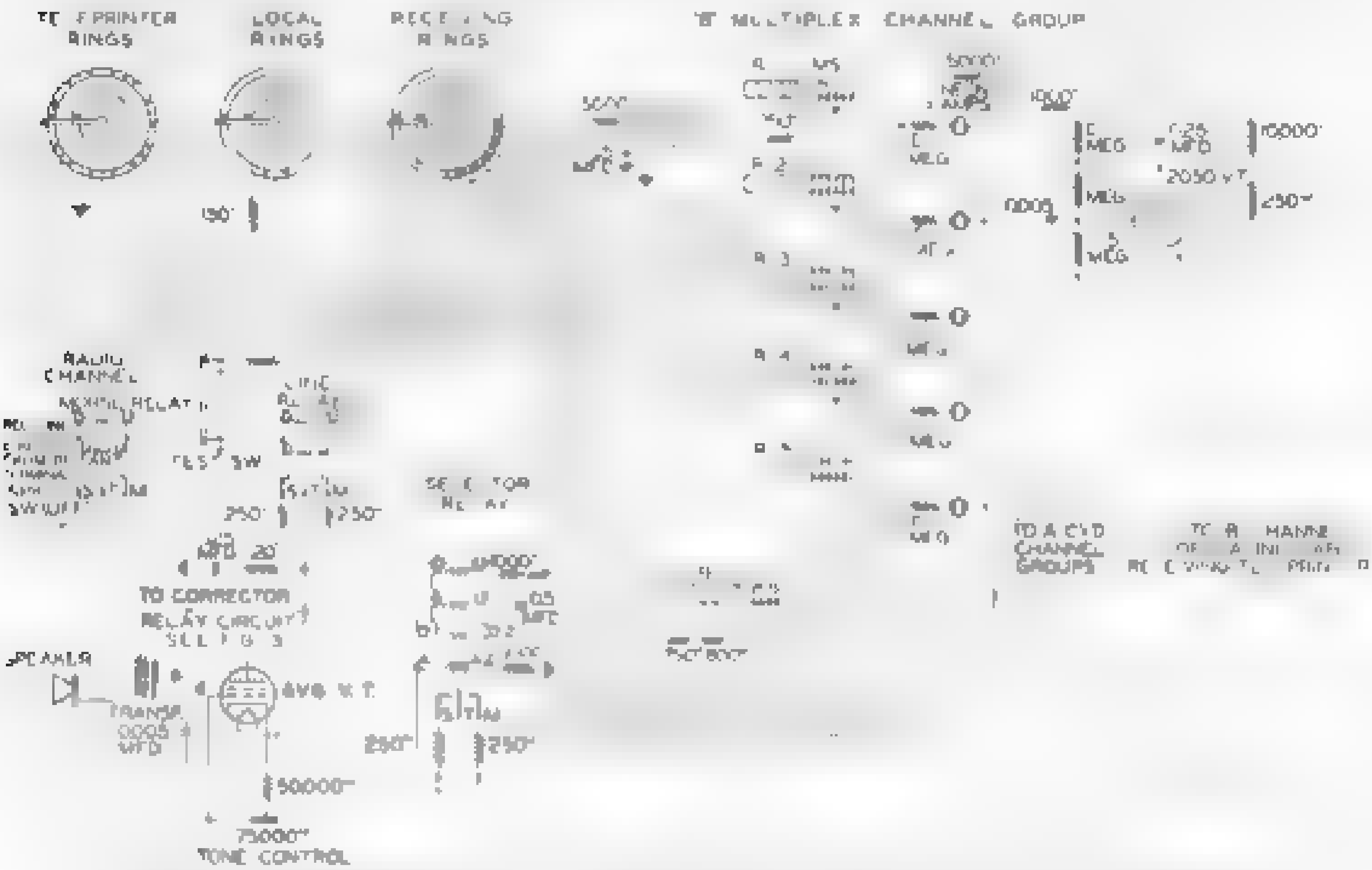

Figure 2. Multiplex system receiving theory showing one of four channels

relays to the grid condenser and grid of the 6V6 tube for that particular signal impulse. If the relay is in its marking position, the condenser will be charged negatively and the tube will be biased to cut-off. The neutral relay in the plate circuit will, therefore, be de-energized. If the selector relay is in the spacing position, the condenser will be charged positively and the tube will pass current. The neutral relay in the plate circuit will then become energized.

Summarizing this operation, the incoming signal operates the line relay which, in conjunction with the receiving rings, operates the selector relay. The selector relay in turn, through the receiving ring, controls the operation of the signal storage relays. During each complete revolution of the brushes, the incoming line signal is broken down into individual signal impulses for each of the four channels which are then set up in the storage relays. The channel relays are operated by the vacuum tubes. The multiplex signals have now been received and stored in the neutral relays and are ready to be sent to the teleprinter associated with the channel. The five-unit code signals must now be converted into seven-unit code signals. This is done by controlling a thyratron tube from seven segments of a third ring on the receiving distributor. Two of these seven segments provide the

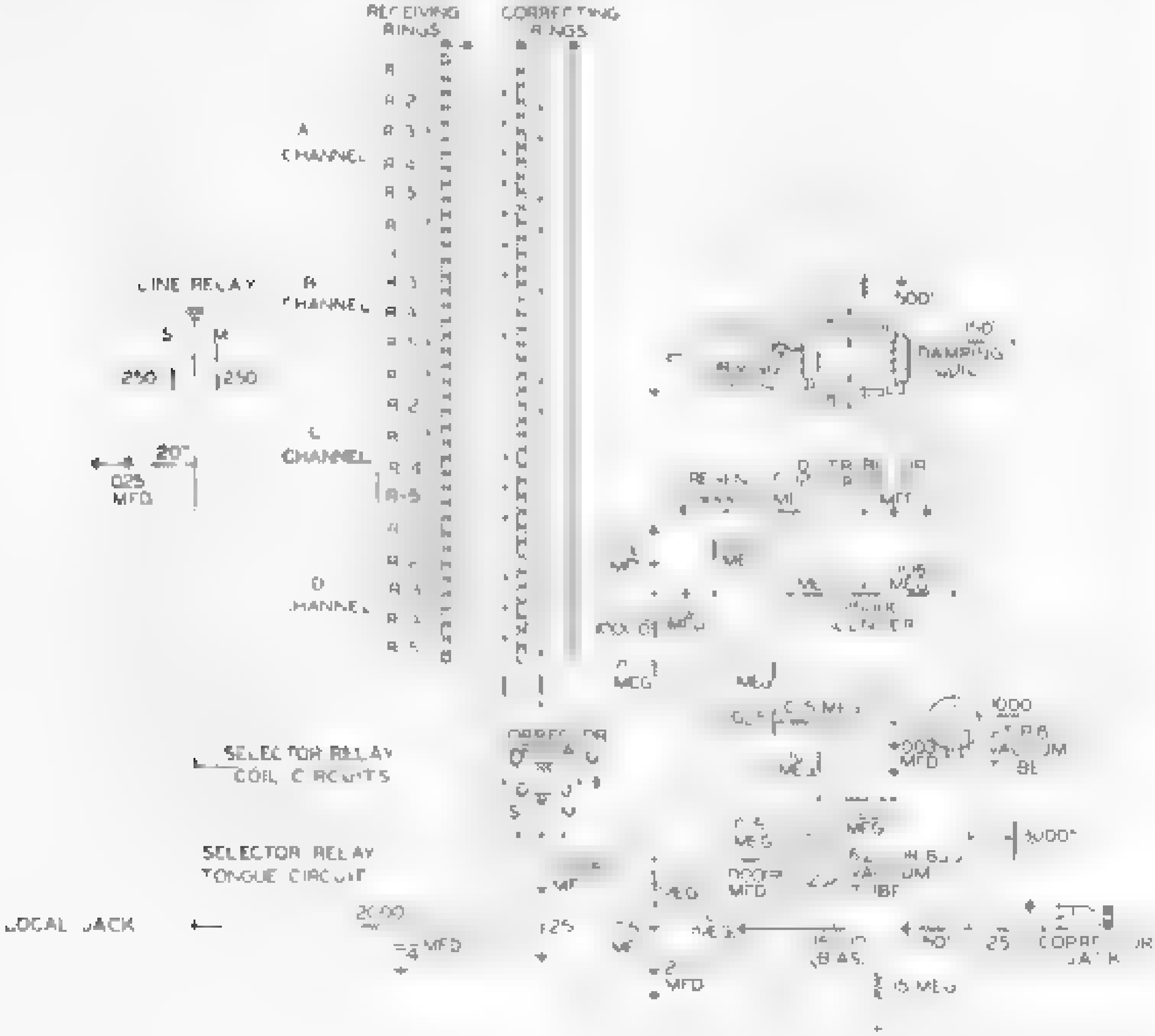

Figure 3. Fork corrector theory

start and stop pulse used in the code, while the other five provide the intelligence pulses. The ring is made up of 28 segments, and the segments are so located that their leading edges will be reached by the brushes, when they are rotating at the proper speed of 360 letters per minute, at 22 millisecond intervals; except that the interval from the leading edge of the following start segment is 35 milliseconds. The thyratron tube and its circuits are so arranged that the thyratron for the channel is made either conducting or non-conducting immediately that the brush reaches the segment, and the length of the segment is not, therefore, a factor in the operation of the circuit. The relationship between the segments of the receiving rings, teleprinter rings and local rings is shown in Figure 2, together with the connections for the B channel. Channels A, C and D are not shown. A functional representation of the teleprinter rings is also shown; that is, the effective length of each of the segments in operating the thyratron tube and thus the receiving printer is indicated.

The neutral relays associated with the channels previously described have two sets of contacts. One set is used to control the operation of the thyratron for the channel, in accordance with the incoming signal, and the other set is used in connection with a relay to cut off the transmission of blanks to the teleprinter when no intelligence is being transmitted over the channel. In order to prevent the transmission of these blanks to the receiving teleprinter, it is necessary to prevent the transmission of the start pulse following the reception of the blank, and this second set of contacts on the channel storage relays with their associated blank cutoff relay and circuits do this.

While the above description outlines the transmission and reception of intelligence in one direction, it can be readily seen that transmission and reception can be carried on simultaneously in both directions, either by means of a grounded duplex system, or by the use of a radio channel in each direction. The loud speaker and its associated relay and tube are used to receive Morse code when testing and regulating the circuit from terminal to terminal. Printers and transmitters are automatically disconnected from the four channels when the control is switched to Morse operation.

In addition to the terminal equipment outlined for handling message traffic between two points, tape repeater equipment was furnished that made it possible to join one or more channels of one radio-multiplex link with another multiplex or radio system without the necessity of manual handling at the junction point of the different systems. Translation equipment was also designed and furnished so it was possible to use standard Navy start-stop cryptographic equipment for transmission to and reception from a multiplex channel.

Navy records show that it was not uncommon to maintain continuous two-way transmission between Washington and Honolulu, and between San Francisco and Guam over periods of 20 to 22 hours out of the day. This enabled them to handle 240 words per minute in each direction on a single radio channel, or four times the number of words possible with a single teleprinter channel. Equal records were established in other radio links where the multiplex system was used. When the war ended the Navy Department was called upon to handle many thousands of telegrams for the Navy Personnel in addition to the heavy load imposed because of official Navy requirements.

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Frequency Translation in Wide-Band Transmission Systems

F. H. CUSACK

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In all that has been written and said about the strides made in the art of communication, a large share of the material has been devoted to those modern methods which provide several channels for simultaneous transmission. The conception which has been considered especially intriguing is the idea that a number of messages or conversations are often scrambled up in seemingly inextricable manner only to be resolved again, mysteriously, but with the greatest of certainty. Of course these mysteries have lost their glamour, at least for those who spend their lives in the development of wide-band transmission systems, and multi-channel operation has become commonplace. Still the problem of utilizing our transmission media to convey intelligence most effectively remains with us, and viewed in this aspect, the results attainable are rather exciting even to the initiated. For example, it is now every-day practice in high-speed carrier telegraphy to transmit something like 600 words per minute for each kilocycle of the total available band width. At this rate, the entire contents of a 500 page text book require only about two minutes of line time on a 150 kc system designed to employ its spectrum with a reasonable degree of efficiency. Such a system can produce a facsimile copy of the text, including all of the illustrations, in 25 minutes. By telephone, speakers of average speed can transmit the same wordage over the system in three-quarters of an hour. Wherever a printed record is required, it must be admitted that telephone is not quite as speedy as this statement implies. Even if a group of readers did convey the text to a group of expert shorthand writers in three-quarters of an hour, it would be quite a while before the notes were transcribed and the material was available in presentable form. But in any terms these figures certainly demonstrate that spectral economy pays off bountifully in terms of message capacity.

Undoubtedly the one factor contributing most to the efficiency so far achieved is the principle of frequency translation, or if you prefer, single sideband transmission. Just how valuable this principle is can be appreciated by examination of Figure 1, which shows the channel layout employed in a 30 kc carrier telegraph system designed for operation over wire

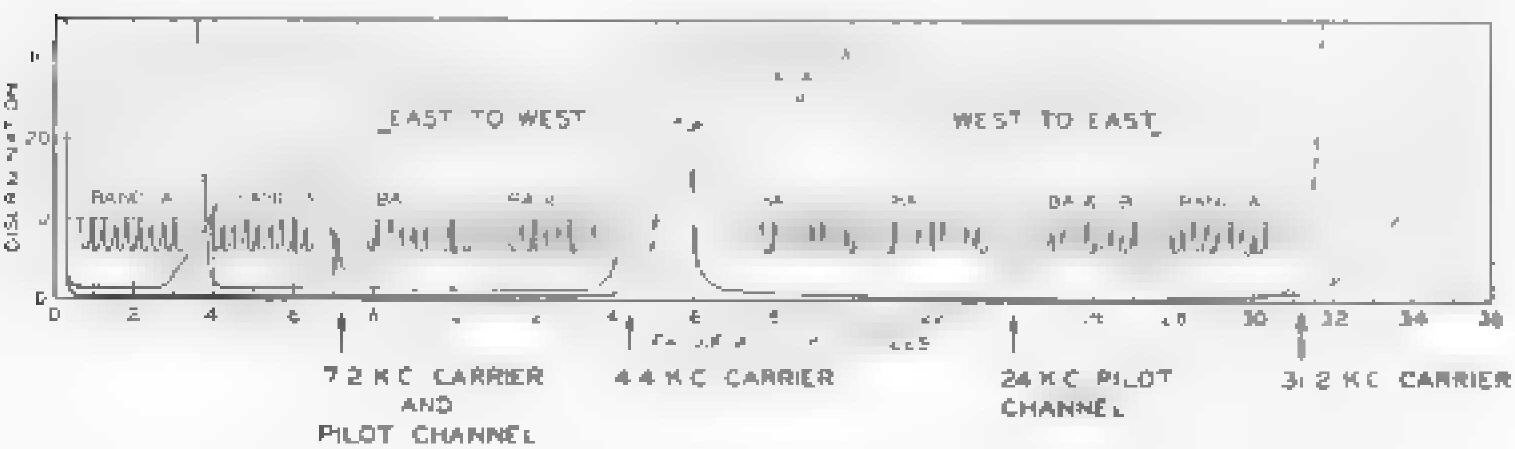

Figure 1. Channel layout—Type G carrier system

lines. In this diagram, the locations of 36 individual telegraph channels are indicated by plotting the discrimination characteristics which would be required of the channel filters if the frequencies were directly generated and individually selected. Since two-way operation is required, they appear at 72 different points in the spectrum. Right away that sounds like a lot of filters, and besides some of them look pretty tough to build. Notice that in the neighborhood of 30 kc we show a filter with the same discrimination needed at the lowest frequencies and with a band width of only 160 cycles, or about a half of one per cent. And that isn't the worst of it. In this system we sometimes want to use channels, suitable for the lower speed services, which are made only 80 cycles wide so that two of them may be substituted for each of the high-speed variety illustrated. Aside from the filter problem, the channels will be frequency-modulated and the control of direct FM for telegraphy becomes extremely difficult at the higher frequencies. In fact, the mere prospect of generating the different carrier currents necessary for such a large number of channels is far from attractive, and of course we do no such thing.

The way out of this dilemma is furnished by the type of modulator called the frequency translator. This device has the very useful property of translating a signal frequency to a new position, higher in the spectrum, in such a manner that the high-frequency signals transmitted over the line occupy a band no wider than that taken by the original signals. Later the process is reversed to translate the received signals back to their original state.

Of all the 72 frequencies shown in Figure 1, only the first nine channels are actually designed and built. The higher frequencies on the line are then secured by translating the basic nine up the scale as desired. The basic group of channels has been made just large enough to constitute a conveniently handled unit. Furthermore, it occupies a band just under 3 000 cycles wide, a band which may readily be employed for telephone or facsimile communication.

Since each band starts out and eventually ends up as a group of basic voice frequencies, an incoming band on one system may be directly cross-connected to an outgoing band on any other system. When circuits are routed over distances sufficiently long to include several carrier systems, each band is regarded as an independent facility linking the system terminals. A group of channels is patched from system to system at will, without considering the line frequencies involved, and without converting the carrier currents back into telegraph impulses until the final destination is reached. In this way, high-speed telegraph circuits are operated from coast to coast with excellent transmission quality and without any relay or regenerative repeaters whatever. Thus, the adoption of the frequency-translation principle results in a situation, rare in engineering practice, wherein the method which is easiest and cheapest to apply turns out also to have fundamental advantages over other possible alternatives.

At this point let us look at what goes on inside the type of modulator commonly used for frequency translation. To satisfy our requirements, this instrument of electrical alchemy must perform the transmutation of a signal frequency into an entirely new frequency without appreciable distortion. Whenever a change occurs in the amplitude, frequency, or phase of the original signal, a replica of this change, or modulation, must also appear at the new frequency. Numerous, indeed, are the schemes which have been proposed to accomplish the purpose. Ideally the circuit arrangement should be such that no unwanted frequencies appear at the output terminals. The frequencies applied to the modulator, the signal and the translating carrier, are both readily suppressed by balance. Still the modulation process inherently insists on producing an upper and a lower sideband, and modulators which have been devised to eliminate one of them are rather involved. The simpler and more common practice is to resort to output filtering to select the desired sideband and reject its unwanted counterpart.

The double balanced modulator of Figure 2 is probably the most popular circuit configuration employed for frequency translation in present day carrier systems. It is a simple bridge network comprising just two transformers and four arrows.

Figure 2. Basic modulator circuit

The arrows may be rectifying elements of almost any type. Dry disc rectifiers, especially copper oxide varistors, have found very wide application in preference to vacuum tube diodes, partly because of their stability and long life, and further because they require no power supply. Recently, the development of rectifying crystals has progressed so rapidly that crystals are now being manufactured with characteristics which rival or surpass those of copper oxide, and with the important additional advantage of very low capacitance. As a result, germanium crystal diodes have now largely replaced copper oxide rectifiers for the purpose. In the modulator circuit shown, the rectifier impedance is expected to vary cyclically between a low resistance and a very high resistance, as dictated by the direction of the polarizing potential supplied by the translating carrier frequency. As we shall see, it is quite important that the carrier alone determine which of these two conditions shall prevail at any time and that the signal be prevented from influencing the decision. When the carrier is in a direction to render longitudinal rectifiers A and B conducting, there is a direct connection between transformers T_1 and T_2, and signal currents flow freely from the input to the output terminals. Rectifiers C and D are now non-conducting. As soon as the direction of the carrier reverses, rectifiers A and B become high resistances and the conducting path from T_1 and T_2 is then through diagonal rectifiers C and D. The result is that the direction of the output current is abruptly turned over every time the carrier reverses polarity. The recurrent shifting of paths between the longitudinal and diagonal connection chops up the output wave in the manner shown in Figure 3 for a low-frequency signal and a high-frequency carrier.

Before going any further, perhaps it would be well to examine the modulated signal momentarily and decide whether it came out as predicted. Does this wave shape contain the two anticipated sidebands and no unwanted frequencies? A simple analysis is sufficient to show that the signal frequency, f_s, and the carrier f_c, as well as harmonics of both, are absent. They have been suppressed by the balanced circuit configuration. It does not follow, of course, that these components

Figure 3. Carrier, signal, and modulator output

have disappeared and may be forgotten forevermore. In practical modulators it is more correct to say that they are of a type to which the circuit offers a degree of balance, so that they may be suppressed as effectively as necessary by controlling

the accuracy of the balance. The same statement applies to all modulation products involving even harmonics of f_s or f_c. As for the useful sidebands $f_c + f_s$ and $f_c - f_s$, it is fairly easy to demonstrate that they are present and even easier to see, just from the square-topped appearance of the wave, that other higher frequencies must also be there. The high-frequency constituents are all members of the family of modulation products which involve odd harmonics of the carrier frequency; $3f_c \pm f_s$, $5f_c \pm f_s$, etc. The largest pair in amplitude, $3f_c \pm f_s$, is less than 10 db below the useful frequencies $f_c \pm f_s$, and a great many of the higher order members of the family are also quite prominent. Nevertheless they are not considered undesirable. On the contrary, the frequencies of this family are purposely accentuated in this type of modulator. They may be readily eliminated by filtering, provided just a little forethought is exercised in the system layout.

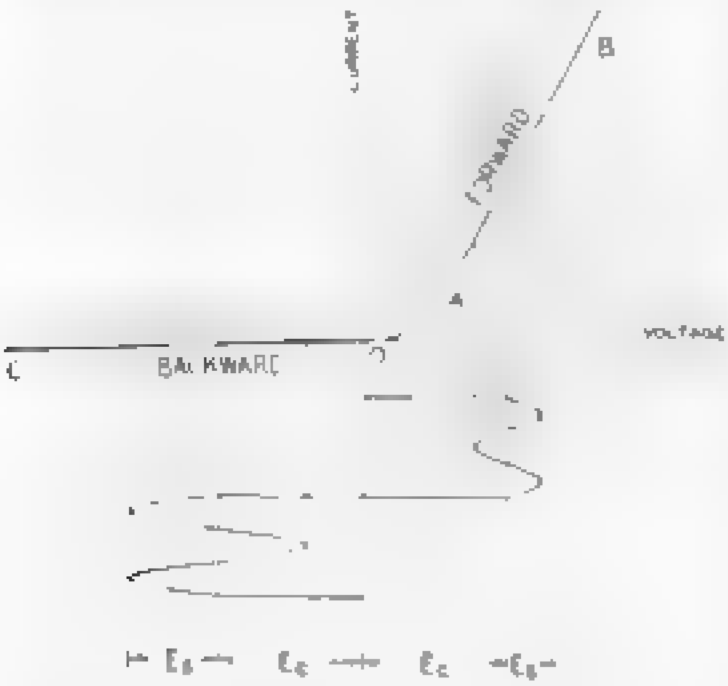

Figure 4. Typical rectifier characteristic

The reason for emphasizing certain modulation products, then filtering them out again, will become apparent when it is seen that this is the inevitable result of the procedure necessary to minimize another family of distortion products, namely those which involve odd harmonics of the signal frequency. It is sometimes inconvenient and often impossible to get rid of such frequencies as $f_c \pm 3f_s$, $f_c \pm 5f_s$, etc., once they have been permitted to appear at the output terminals of the modulator. Modulation products in this family cause distortion in the reception or interchannel interference. A particularly distressing example is the disturbance introduced by an active carrier band into some other quiet band intended for telephone service.

The source of the modulation products involving harmonics of the signal frequency will be discussed with the aid of Figure 4. The upper portion of this illustration shows the current-voltage characteristic of a typical rectifying element. When voltage is applied in the forward, or conducting, direction the rectifier is not truly a constant low resistance. Rather it has a characteristic somewhat as indicated by the line OAB. From the origin O to a region in the vicinity of A the characteristic is definitely non-linear; then from A to B and beyond it is nearly a straight line. In the backward, or non-conducting, direction it may be considered for the moment as a high resistance characterized by the line OC. Whenever the carrier polarizes the rectifier in the forward direction, any signal riding through on top of the carrier encounters a constant resistance just so long as the summation of signal and carrier voltages remains within the linear portion of the characteristic. But during the part of the carrier cycle in which the rectifier is being switched between its conducting and non-conducting conditions, the non-linear portion of the characteristic cannot be avoided. Within this interval, the signal is distorted because the rectifier impedance is not controlled exclusively by the carrier but depends in part upon the signal voltage. The result at the output terminals is the same as though the input signal had contained odd harmonics (the evens being suppressed by balance), and the modulated signal contains the distortion products $f_c \pm 3f_s$, $f_c \pm 5f_s$, etc.

Distortion in the modulated signal can be reduced either by increasing the carrier amplitude or by decreasing the signal level. The extent to which low signal levels can be employed is limited by noise conditions, and also by the amplifier gain

conveniently obtainable to restore the modulated signal to a suitable level. The maximum permissible carrier amplitude is simply the value considered safe for the rectifier units. As portrayed in the lower part of Figure 4, the advantage of a very large carrier current can be secured, without exceeding the safe limit, by using a square wave instead of a sinusoidal carrier. The square-topped carrier voltage, E_c, is assumed to reverse its direction very suddenly, thereby switching the rectifier abruptly from its non-conducting condition to the linear portion of its conducting characteristic. If the reversal is truly instantaneous, the signal voltage, E_s, will never encounter the non-linear part of the curve and the distortion will be reduced to a very small minimum.

A modulator of the type shown in Figure 2 is admirably suitable for frequency translation and can be so operated as to perform essentially without distortion. Still the signal levels must be kept quite low, particularly where a large number of channels are handled simultaneously, and this restriction is often rather inconvenient. The paragraphs which follow will consider the factors which determine the overload point of this modulator and will describe a simple expedient which has been devised to increase its undistorted power output.

For the particular value of E_c illustrated by Figure 4, it is evident that E_s may be made somewhat larger than shown without overloading. In fact, it might be inferred from the previous discussion that distortion will not become excessive unless the signal peaks are large enough to swing over into the curved portion of the rectifier characteristic. Examination of conditions existing in the non-conducting direction will soon reveal that such is not the case. In Figure 4 the signal voltage, E_s, is shown considerably larger in the backward direction than in the forward direction, while the carrier voltage, E_c, is the same in both directions. This relationship is an inherent characteristic of the circuit. It causes the non-conducting rectifiers to overload at signal levels which are considerably less than the safe capacity of the conducting units.

Fortunately, it is possible to examine the problem in some detail without taking an excursion into the higher mathematics of modulation. The simplified equivalent circuit of Figure 5 ignores the refinements and assumes an ideal rectifier which is either a low resistance, R_f, when polarized in the forward direction, or a high resistance, R_b, when the carrier is applied in the backward direction. The diagram illustrates the case where the longitudinal branches are conducting and the diagonals are non-conducting, but the reasoning which follows is also applicable when the carrier reverses and the positions of R_f and R_b are interchanged

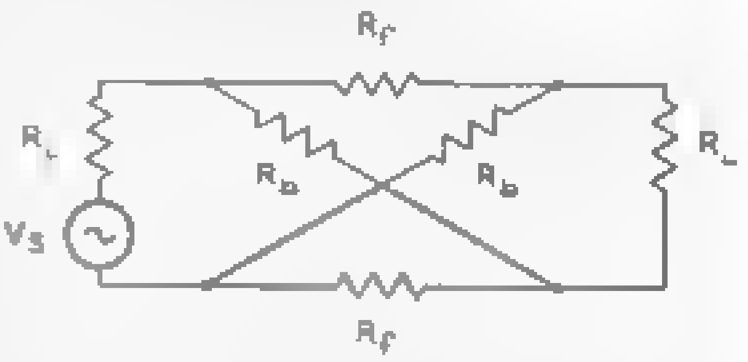

Figure 5. Equivalent modulator circuit

Considering first the voltages applied to a conducting rectifier, the signal component is

$$E_s = V_s \frac{R_f}{2\,(R_L + R_f)}$$

The carrier voltage across a conducting rectifier element is

$$E_c = \frac{I_c}{2} R_f$$

Where I_c is the total carrier current.

If the carrier has a perfectly square-topped wave form, the idealized rectifier will not be overloaded until the signal peaks become large enough to exceed the carrier amplitude. The peak value of the maximum permissible input signal is thus found by equating E_s and E_c, and solving for V_s. The result is

$$V_s\ (\text{max.}) = I_c\ (R_L + R_f) \qquad (1)$$

While the conducting branches will not be overloaded unless V_s exceeds the value of Equation (1), it remains to obtain a

similar solution for the non-conducting rectifiers. Here

$$E_c = \frac{I_c}{2} R_f, \text{ as before.}$$

But the signal voltage across a non-conducting branch is

$$E_s = V_s \frac{R_b}{2\,(R_L + R_b)}$$

or $E_s = \frac{V_s}{2}$, as a very close approximation

Solving for the overload value of V_s gives, in this case,

$$V_s\ (\text{max.}) = I_c\, R_f \qquad (2)$$

Obviously the voltage in Equation (2) is much smaller than that in Equation (1) and so is the first to be exceeded as the signal input is increased. In a typical case, R_L may be as much as 600 ohms and R_f only about 50 ohms, so that the non-conducting rectifiers will overload with a signal less than one-tenth of that required to overload the conducting branches.

Just as soon as the limiting condition has been correctly recognized, methods for increasing the undistorted power output of such a modulator begin to suggest themselves. Evidently it is only necessary to devise a scheme for raising the back carrier voltage applied to the rectifiers, and thereby prevent the large signal peaks in this direction from breaking through the polarizing wave. In this way overloading of the non-conducting branches can be deferred until the conducting branches are also loaded to capacity. If the basic circuit is so modified that carrier is fed to the longitudinal and diagonal branches separately, the carrier voltage can be made greater in the backward than in the forward direction by means of asymmetrical generators, biasing batteries, or self-biasing resistors. A simple example is shown in Figure 6, where the input transformer has been provided with two identical secondary windings which are connected separately to the pairs of rectifiers. Carrier is then fed to the two branches through a center-tapped resistor, R_n.

All of the voltage relationships previously derived are also valid for this circuit except that the carrier voltage across a non-conducting rectifier has been increased and is now

$$E_c = I_c \frac{R_n}{2} + \frac{I_c}{2} R_f$$

$$\text{or } E_c = \frac{I_c}{2}\,(R_n + R_f)$$

The solution for the input signal which is just sufficient to overload the non-conducting branches yields the result,

$$V_s\ (\text{max.}) = I_c\ (R_n + R_f) \qquad (3)$$

The corresponding expression for the conducting elements remains unchanged and is

$$V_s\ (\text{max.}) = I_c\ (R_L + R_f) \qquad (1)$$

From Equation (3) it is apparent that as R_n is increased, the load capacity of the non-conducting branches is also raised until finally a condition is reached where the conducting and non-conducting elements will overload simultaneously. This occurs when Equations (1) and (3) are equal or when R_n is made equal to R_L. No additional improvement results from a further increase of R_n.

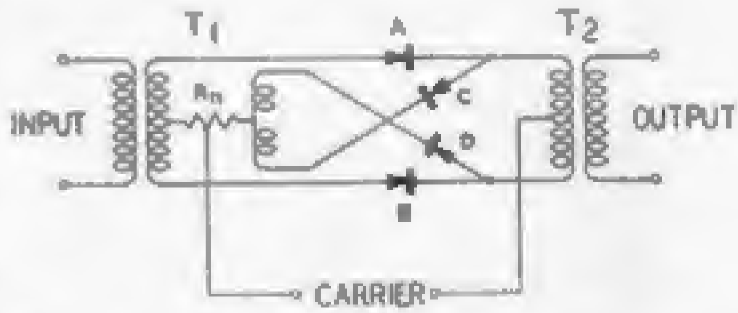

Figure 6. Modulator with external resistor

Another simple scheme for increasing the modulator load capacity is illustrated in Figure 7, which differs from the basic modulator only in the addition of a resistor R_s in series with each rectifier. These resistors serve to raise the carrier voltage applied to the rectifiers in the reverse direction just as effectively as the external resistor of Figure 6. Because they are inserted in the signal path, the internal resistors introduce some loss, but they boost the permissible power output sufficiently to result in a net improvement. They also simplify the problem of balanc-

ing the modulator for carrier suppression, and tend to reduce the distorting effect of any slight curvature in the rectifier characteristic.

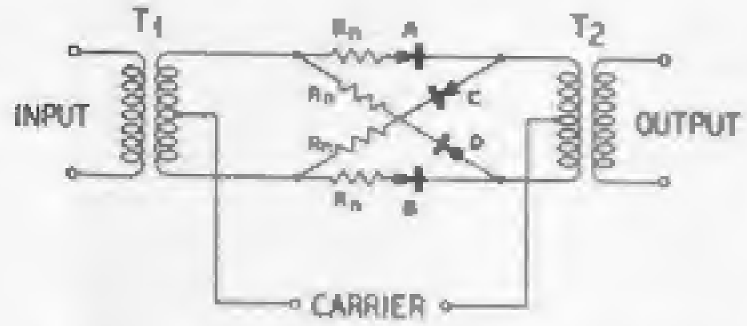

Figure 7. Modulator with internal resistors

In designing a modulator for a specific application, it is usually possible to improve its performance greatly by using either internal or external means to employ the above principle. It will not be possible to discuss the subject here at greater length, but it may be of interest to mention that modulators have been built in which the power-carrying capacity has been raised in this way by as much as 20 db. By allowing signal levels to be increased correspondingly, the margin between signal and interference is widened and the need for accompanying amplification is reduced or eliminated altogether.

When the time comes to lay out the terminals of a carrier system, all sorts of problems must be studied before the locations of the frequency bands are finally decided upon and the translating carrier frequencies selected. Modulation products which might cause interchannel interference must be avoided, while at the same time attaching proper importance to the efficient utilization of the available frequency spectrum. We have already seen that spectral economy is a fundamental characteristic of the frequency-translation process, but in practice, one rather perplexing difficulty remains to be solved before a large number of channels can be spaced at close frequency intervals.

As an example of the kind of thing that happens, suppose several voice-frequency bands are to be transmitted. Using round numbers for illustration, the first band will lie within the frequency interval below 3 kc, and the second may be translated upward to the space between 4 and 7 kc by means of modulation. A guard band between 3 and 4 kc is necessarily wasted because of the properties of the filters required to separate the bands. Selective networks do not pass equally all frequencies within a specified band and then abruptly reject all other frequencies. They can be designed with a very sharp cut-off but nevertheless do consume a certain frequency space in passing from minimum to maximum attenuation, and this segment of the spectrum is therefore lost.

Continuing to add to the above system, the next two carrier bands would go between 8 and 11 kc and from 12 to 15 kc, and one might conclude that the process could be continued indefinitely. Unfortunately the waste of spectrum becomes increasingly great if direct modulation is employed in this manner. For a given type or quality of selective circuit, the relative sharpness of cut-off is roughly proportional to the frequency and, as a result, large frequency intervals are lost at the junctions between bands located high up in the spectrum. A guard band of 10 per cent would not be considered excessive in the vicinity of 10 kc where the resulting gap is only one kilocycle wide. But at 100 kc a 10 per cent wastage amounts to a band 10 kc wide, and this is a frequency space of considerable economic value.

An interesting scheme has been worked out to reduce the waste of spectrum by performing frequency selections, in so far as possible, in the low frequency range. In this method, the system terminal is arranged in the form of a pattern in which the number of channels is successively increased by convenient multiples. For example, the second carrier band might be derived by translating the basic frequencies to an adjacent position above the first, but direct modulation need not be used beyond that point. Instead, the next two bands could be obtained by repeating the above process and then translating the third and fourth bands upward simultaneously in an additional modulator. To add four more bands, the same thing would be done all over again, and then a group modulator would be pro-

vided to translate this second group to its assigned higher frequency location. Thereafter the pattern may be continued by similarly doubling the system capacity with each succeeding stage of modulation.

In Figure 8 is shown the result of applying this method in the design of a carrier system intended to fill a 30 kc band width. Here the pattern is built up in three successive stages to secure eight voice bands. Starting off with modulators supplied with a carrier frequency of 7.2 kc, the basic frequencies from .3 to 3.3 kc are moved to a location between 3.9 and 6.9 kc. The lower sideband is selected in this, and also in the following stages of modulation. Next a group modulator

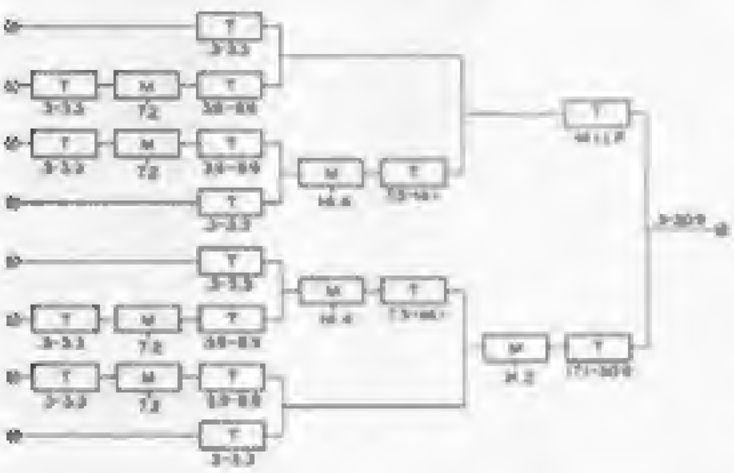

Figure 8. 30 Kc system—block diagram of one terminal

with a 14.4 kc carrier translates the range from .3 to 6.9 kc to the interval between 7.5 and 14.1 kc. Finally, the frequencies between .3 and 14.1 kc are converted into frequencies between 17.1 and 30.9 kc by a group modulator using a carrier of 31.2 kc.

With one exception, the guard bands in this system are only 600 cycles wide, even at the highest frequencies. Between 14.1 and 17.1, there is a guard band which wastes 3 kc of the spectrum, but this has been made twice as wide as necessary for another reason. In Figure 8 the equipment is shown as arranged for four-wire working. It would be used in this way to transmit over a radio circuit, where a separate radio link would be operated in the opposite direction. However, the same equipment is also employed for two-wire working over land lines to provide the carrier system previously shown in Figure 1. In this case, half of the available spectrum is used in one direction and the remainder is reserved for the return circuit. The filters which separate the directional frequencies at the terminals and repeaters must be given an increased guard band, especially if the system is to be operated through a number of repeater sections in tandem.

Even with this one rather wasteful gap, the system is exceptionally economical of its spectrum space. If direct modulation had been employed for all eight carrier bands, the wastage charged to guard bands would have been just about doubled. It would also have been necessary to design a greater number of different filters and to provide eight different carrier frequencies instead of only three.

When the terminal pattern is further extended to fill up a wider band, the savings become still more spectacular because of the way each added stage of modulation doubles the system capacity. This feature makes the scheme particularly valuable when dealing with a modern wide-band transmission medium. An interesting example is a microwave radio relay system from which a band width of approximately 150 kc is derived. By using five successive stages of modulation, 32 voice bands are put into this space, and in most cases the bands are less than one kilocycle apart. Of course this sort of performance can be duplicated by more costly means, but here it is accomplished with selective networks of a relatively simple, inexpensive design. Significant economies result from the fact that only seven different types of filters and five different carrier frequencies are required to obtain the 32 bands.

In conclusion, it might be well to point out that the frequency translation principle exacts a certain price for the advantages it affords. It is truly essential that single side-band, suppressed carrier transmission be employed if the available spectrum is to be used with any reasonable degree of economy. But obviously the channel frequencies received over such a system are not going to be quite the same as those transmitted unless the translating carrier frequencies at both ends

are matched exactly. This consideration makes it necessary that the carrier oscillators possess a much higher degree of frequency stability than that needed anywhere in a double sideband system in which the carrier is not suppressed. Furthermore, the requirements are somewhat more exacting for carrier telegraphy than for telephone service.

In a carrier telegraph system it is customary to keep the absolute frequency variation of the local carrier supply below one cycle. The percentage of frequency stability depends on how high the modulating frequency is to be. Systems operating below 15 kc may be permitted a tolerance of one part in 20,000, while the oscillators for a 150 kc system must be made stable within one part in 200,000. It will suffice to say that these limits have been met without encountering insurmountable obstacles. Present day systems work along continuously and reliably without any need to check synchronism between the terminals except at infrequent intervals and in a routine manner.

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